反陽子ヘリウム原子分光で

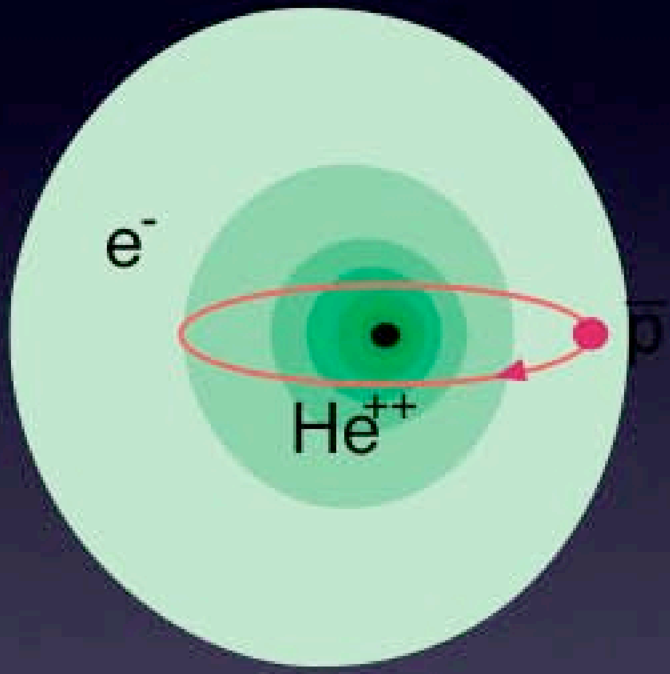
反陽子の重さを量る

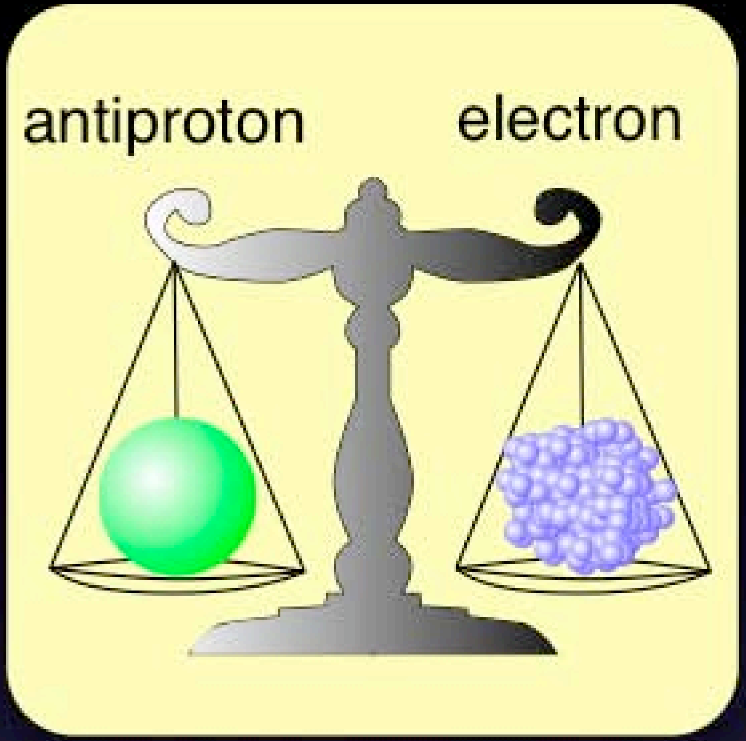
早野 龍五

The University of Tokyo

THE UNIVERSITY OF TOKYO

RIKEN Colloquium, Oct 16, 2007


e-
p
He++



↓

CPT定理

↓

陽子・電子質量比

PRL **96,** 243401 (2006) PHYSICAL REVIEW LETTERS week ending 23 JUNE 2006

Determination of the Antiproton-to-Electron Mass Ratio by Precision Laser Spectroscopy of $\bar{p}\mathrm{He}^+$

M. Hori,[1,2] A. Dax,[2] J. Eades,[2] K. Gomikawa,[2] R. S. Hayano,[2] N. Ono,[2] W. Pirkl,[2] E. Widmann,[3] H. A. Torii,[4] B. Juhász,[5,3] D. Barna,[6,2] and D. Horváth[6]

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(Received 10 April 2006; published 19 June 2006)

Antiprotonic helium and CPT invariance,
R.S. Hayano, M. Hori, D. Horvath, E. Widmann,
Reports on Progress in Physics 70, 1–74 (2007)

始

introduction

(&conclusion)

陽子の質量は電子質量の約1800倍
(理科教科書)

もうちょっと詳しく言うと
(理科年表)

陽子質量は電子質量の

1836.1526725 倍

1 2 3 4 5 6 7 8 9 10 11

電子との質量比

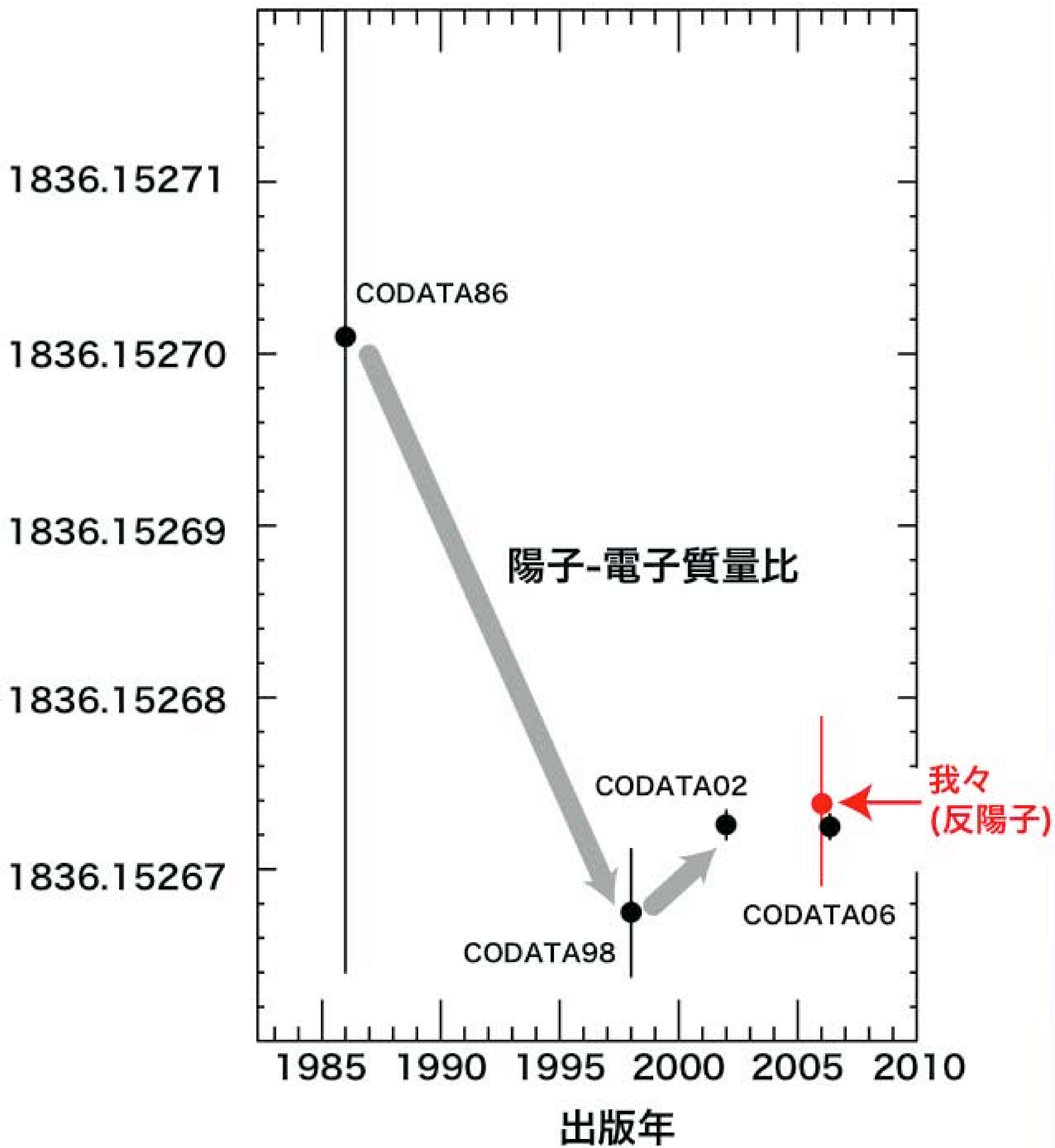
1 2 3 4 5 6 7 8 9 10

	陽子	1836.1526725
我々2006→	反陽子	1836.152674
		±0.000005

9桁目までは完全に一致

10桁目も誤差の範囲で一致

グラフで示すと

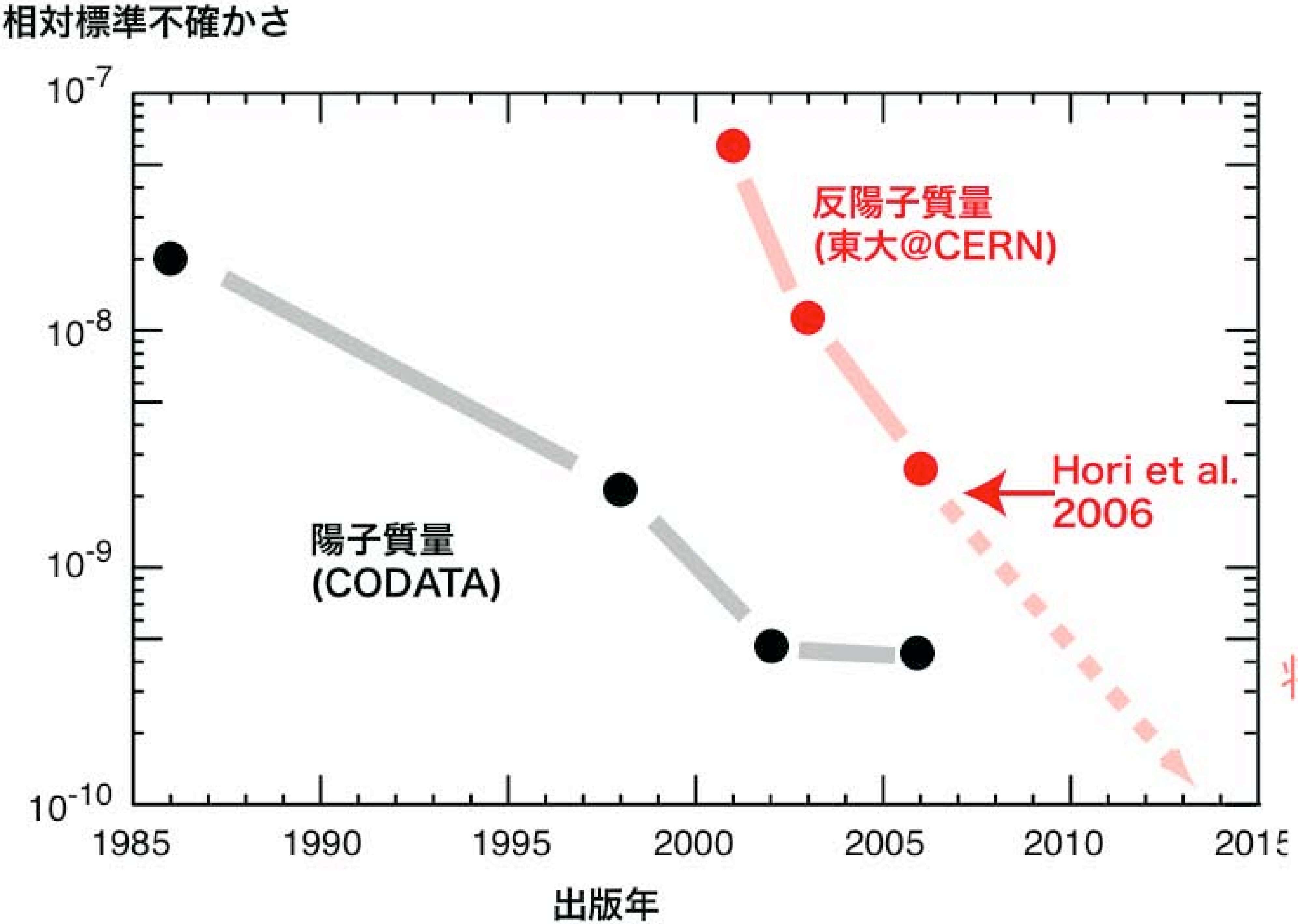


1. 物質・反物質対称性の精密検証

2. 基礎物理定数への貢献

近未来の可能性

“理科年表更新”



まだ
５倍負けているが
将来逆転 … するぞ！

基礎物理定数の例

CODATA 2006より

（単位系に深く関係している）

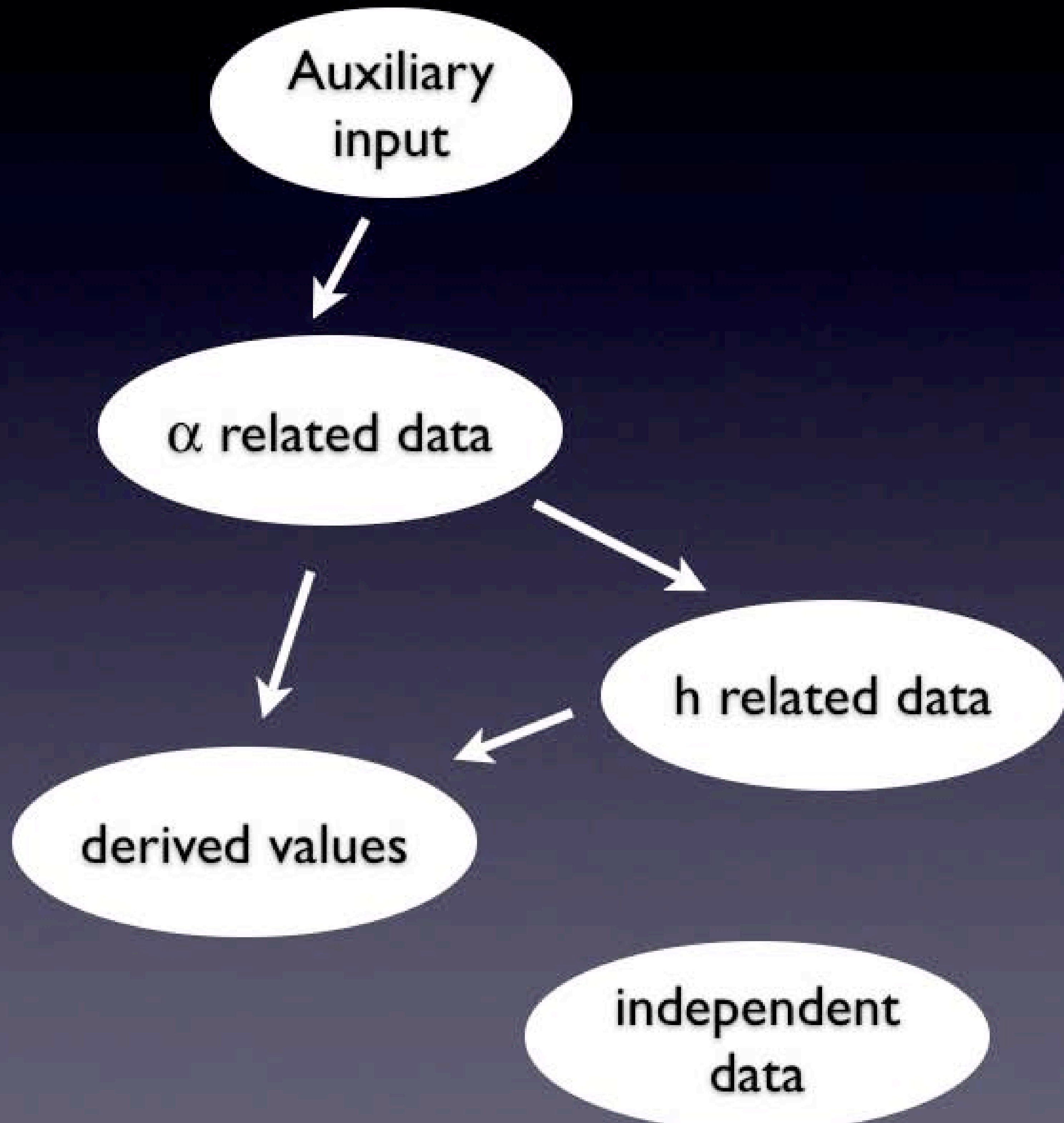
ppb=10億分の1

物理定数	数値 (下線の桁に不確定性がある)	単位	精度	
光速	299 792 458	m s^{-1}	定義値	
万有引力定数	6.674 3	x 10^{-11} m^3 kg^{-1} s^{-2}	5桁	100000 ppb
アボガドロ数	6.022 141 8	x 10^{23} mol^{-1}	8桁	50 ppb
プランク定数	6.626 068 9	x 10^{-34} J s	8桁	50 ppb
陽子の質量	1.672 621 64	x 10^{-27} kg	9桁	50 ppb
電子の電荷	1.602 176 49	x 10^{-19} C	9桁	25 ppb
陽子・電子質量比	1836.152 672 5		11桁	0.43 ppb
リュードベリ定数	10 973 731.568 52	m^{-1}	13桁	0.0066 ppb

T.W. Hänsch et al., hydrogen spectroscopy using frequency comb, Nobel Prize 2005

CODATA adjustment flowchart

from S.G. Karshenboim



Auxiliary data = the most accurate data which are to be evaluated prior to the adjustment, R_∞, $\underline{m_e/m_p}$, ...

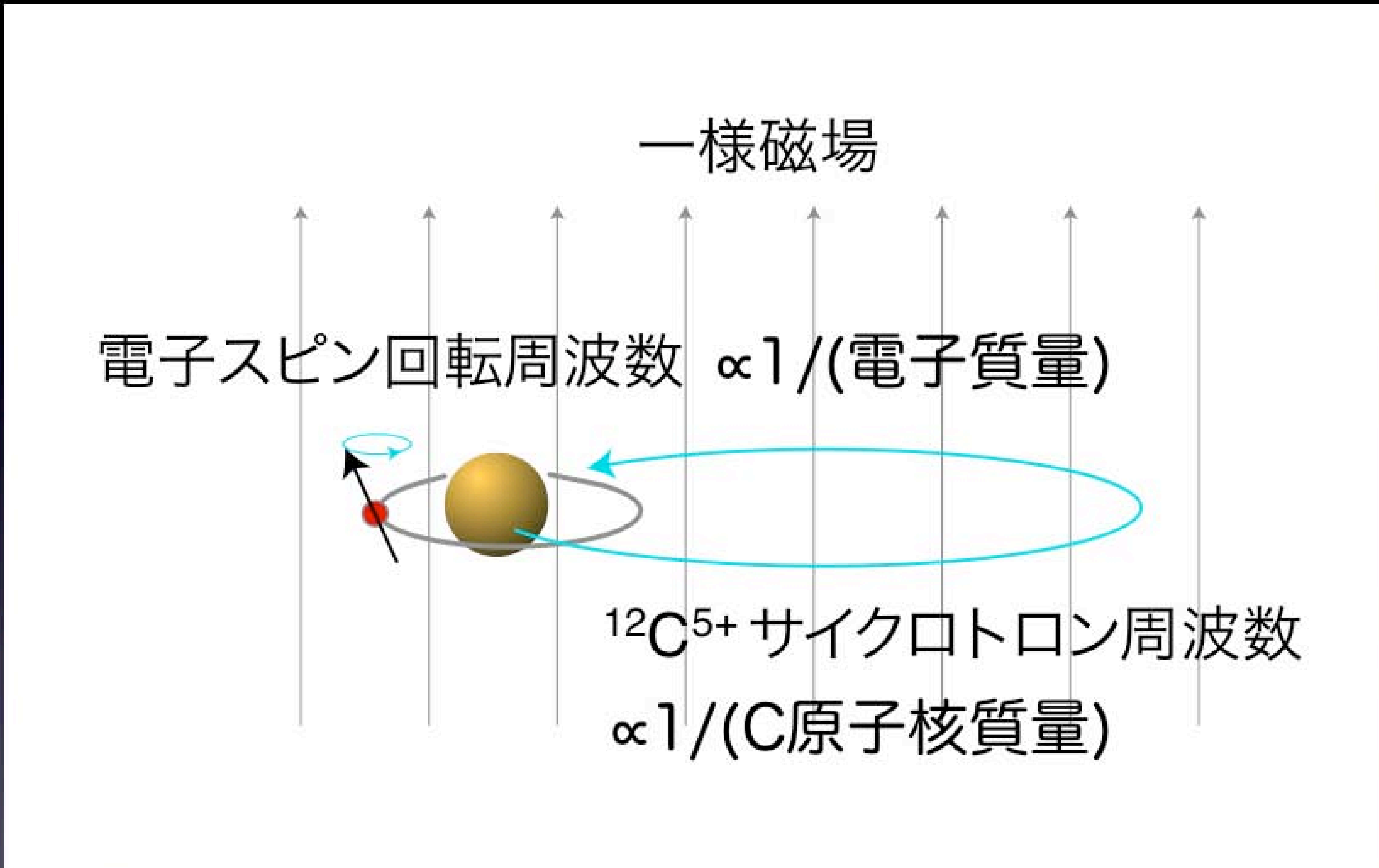
Arrows are equations

Derived: m_p [kg], m_e[MeV/c^2], etc...

ちなみに

m_p/m_eはどうやって量っているか

Beier et al, PRL 88 (2002) 011603



二つの周波数の比→量子電磁力学補正→
C原子核と電子の質量比→陽子・電子質量比

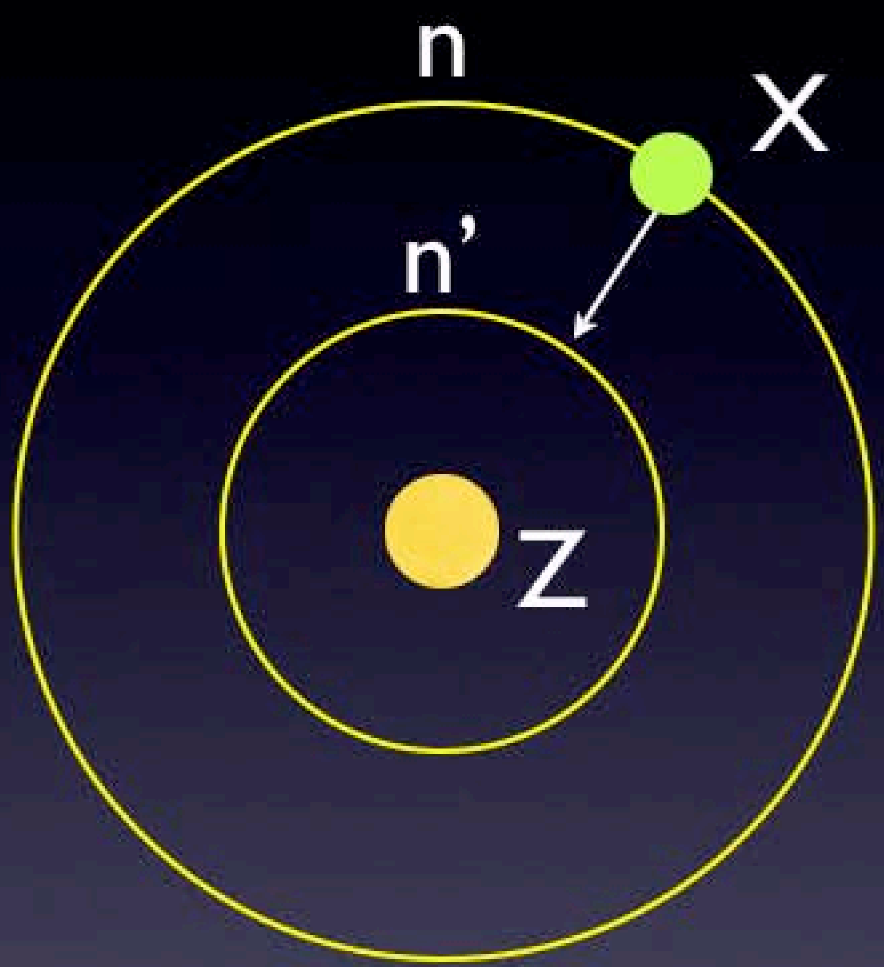
陽子のようにありふれたものですら、質量を10桁以上の精度で決めるのは容易でない

反陽子のように自然界に存在しないものの質量をどうやって測定するの？

素粒子の質量 (PDG)

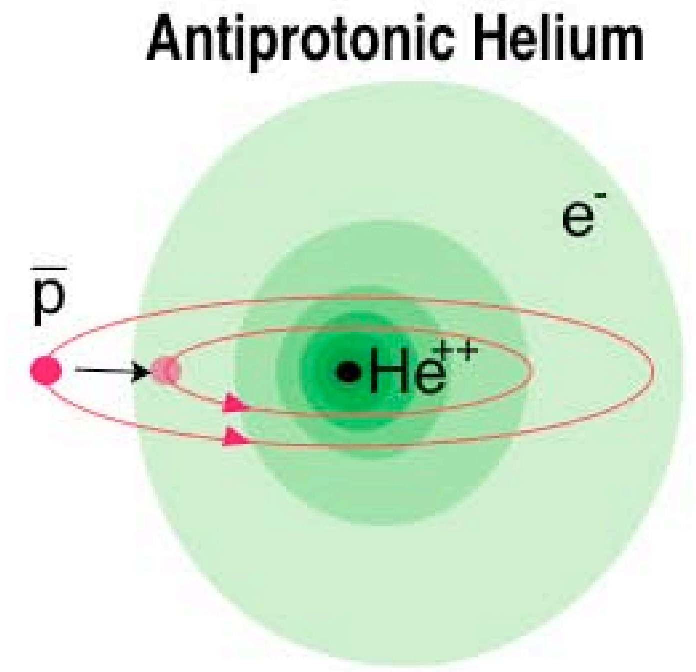
Particle	How?	eV/c^2 での精度 ppm	u での精度ppm
e^-	Penning trap	0.078	0.00044
p	Penning trap	0.085	0.00013
μ^+	μ^+e^- laser, HFS	0.085	0.027
π^-	X-ray	2.5	-
K^-	X-ray	32.4	-

Exotic atomの脱励起



$$\Delta\nu_{n,\ell\to n',\ell'} = Rc\frac{m_X^*}{m_e}Z^2\left(\frac{1}{n'^2}-\frac{1}{n^2}\right)$$

Laser resonance to change $\bar{p}$ orbit → $\bar{p}$ - e mass ratio



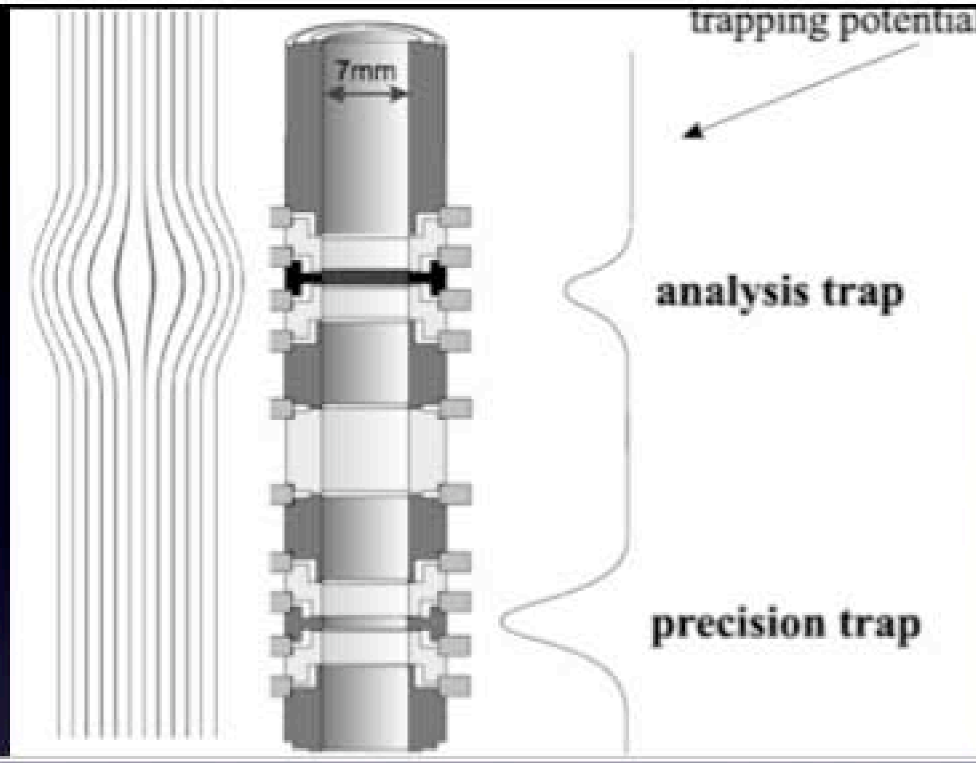
For antiprotonic helium $(\bar{p} + e^- + \alpha)$,

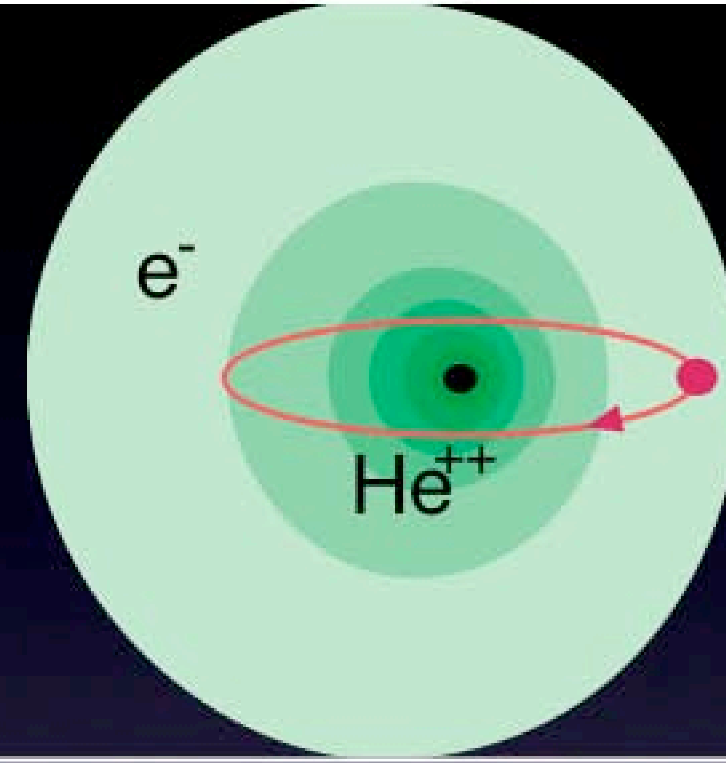
$$\nu(n, n') = Rc \frac{M^*_{\bar{p}}}{m_e} Z^2_{\text{eff}} \left(\frac{1}{n^2} - \frac{1}{n'^2} \right)$$

Would be exact for $\bar{p}$He ion
approximate for the 3-body system

Z^2_{eff}: helium charge, shielded by electron (calculated by theory)

+relativistic correction
+QED correction
+ hyperfine



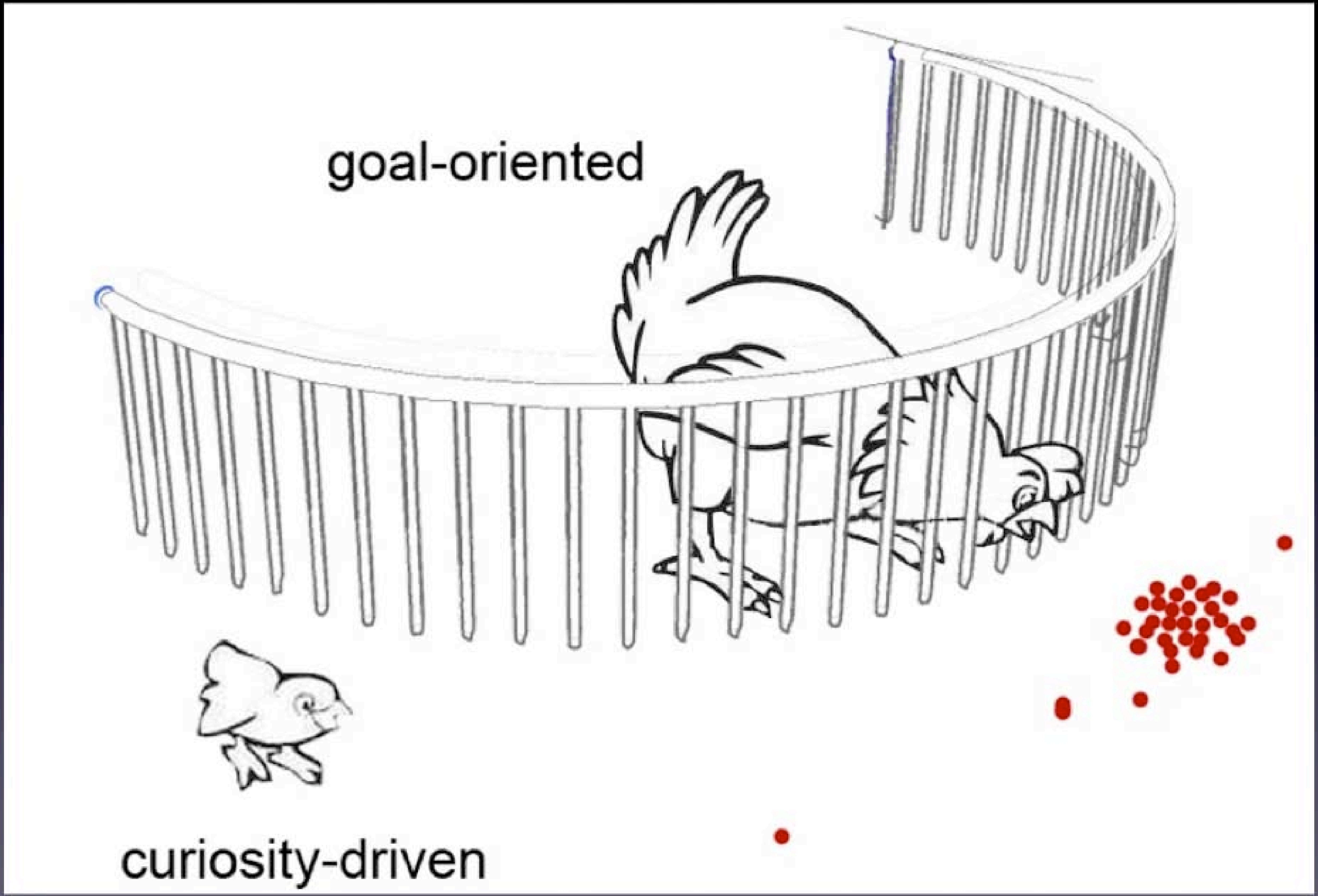


Penning trap:
man-made trap

Antiprotonic helium:
naturally-occuring
trap

しかし我々は最初から

m_p/m_e測定を目指したのではない



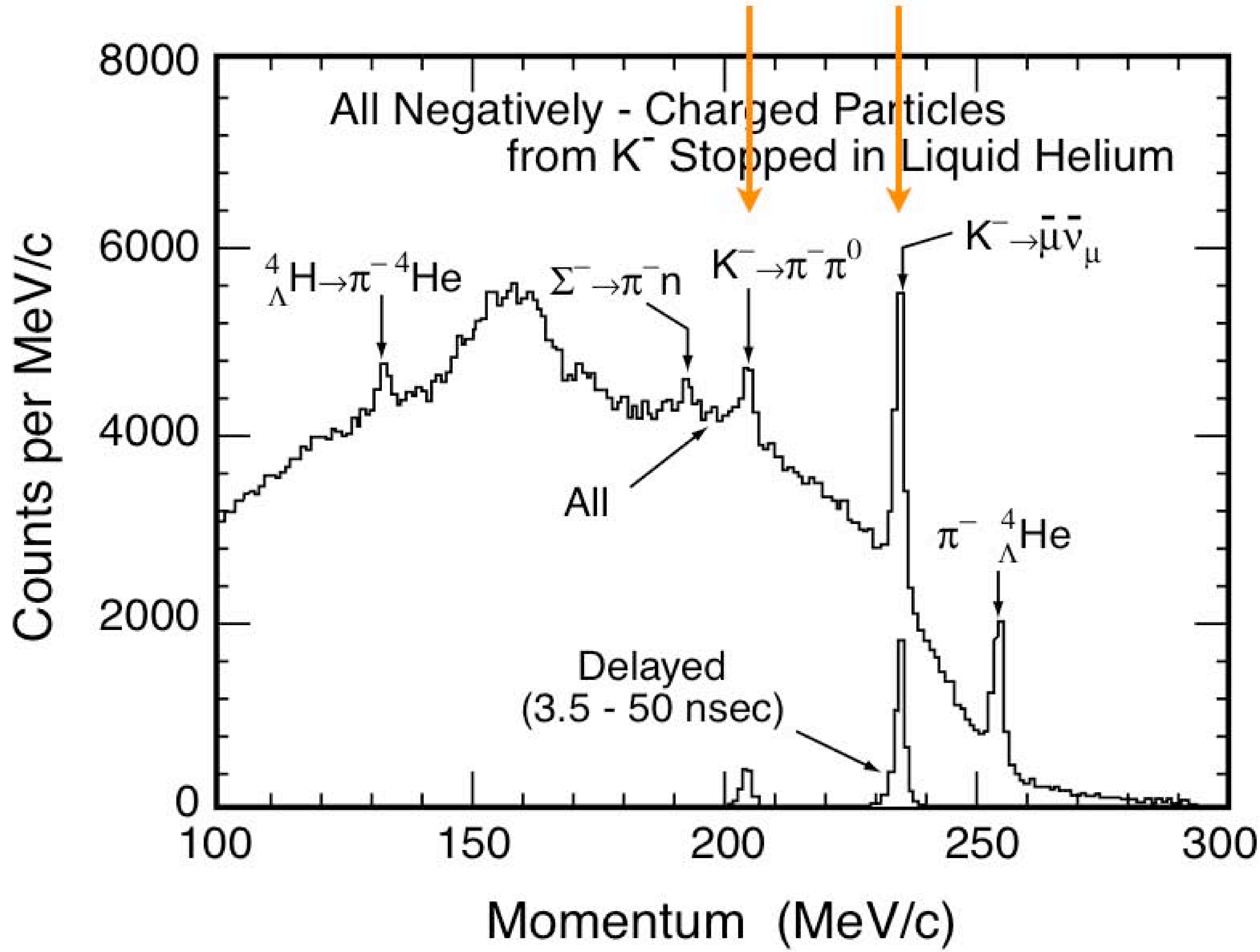
T.W. Hänsch, nobel lecture 2005

歴史

Historical

ハイパー核研究
液体ヘリウムに止めたK^-

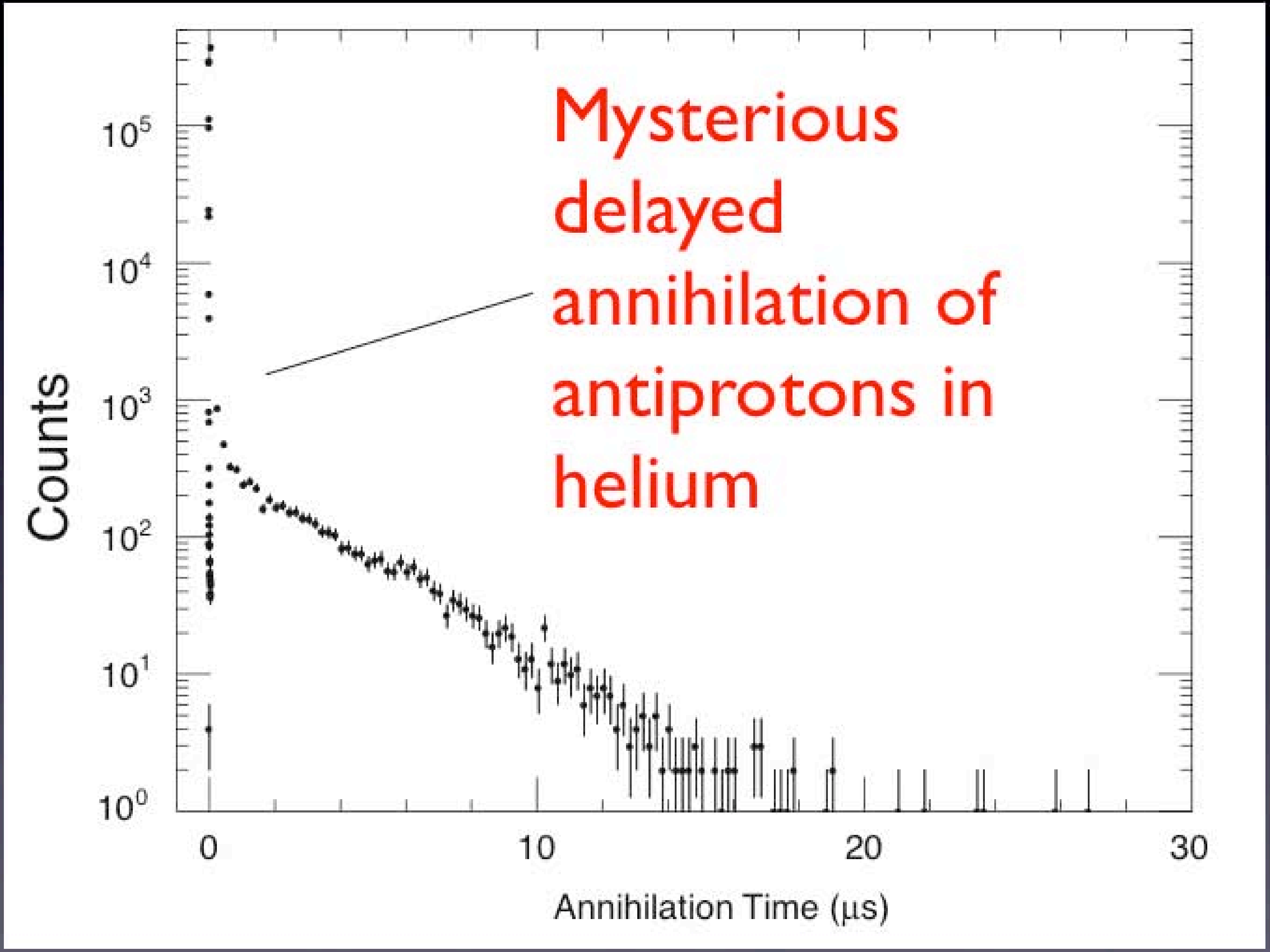
Kaon weak decay peaks



R. S. Hayano et al, Phys. Lett. B 231 (1989) 355 how can K^- weak decay (lifetime 12ns) be visible when cascade & nuclear capture can be as fast as <1ns?

これは異常だ
反陽子でも異常が見えるか？

Serendipitous discovery of naturally-occurring $\bar{p}$ trap



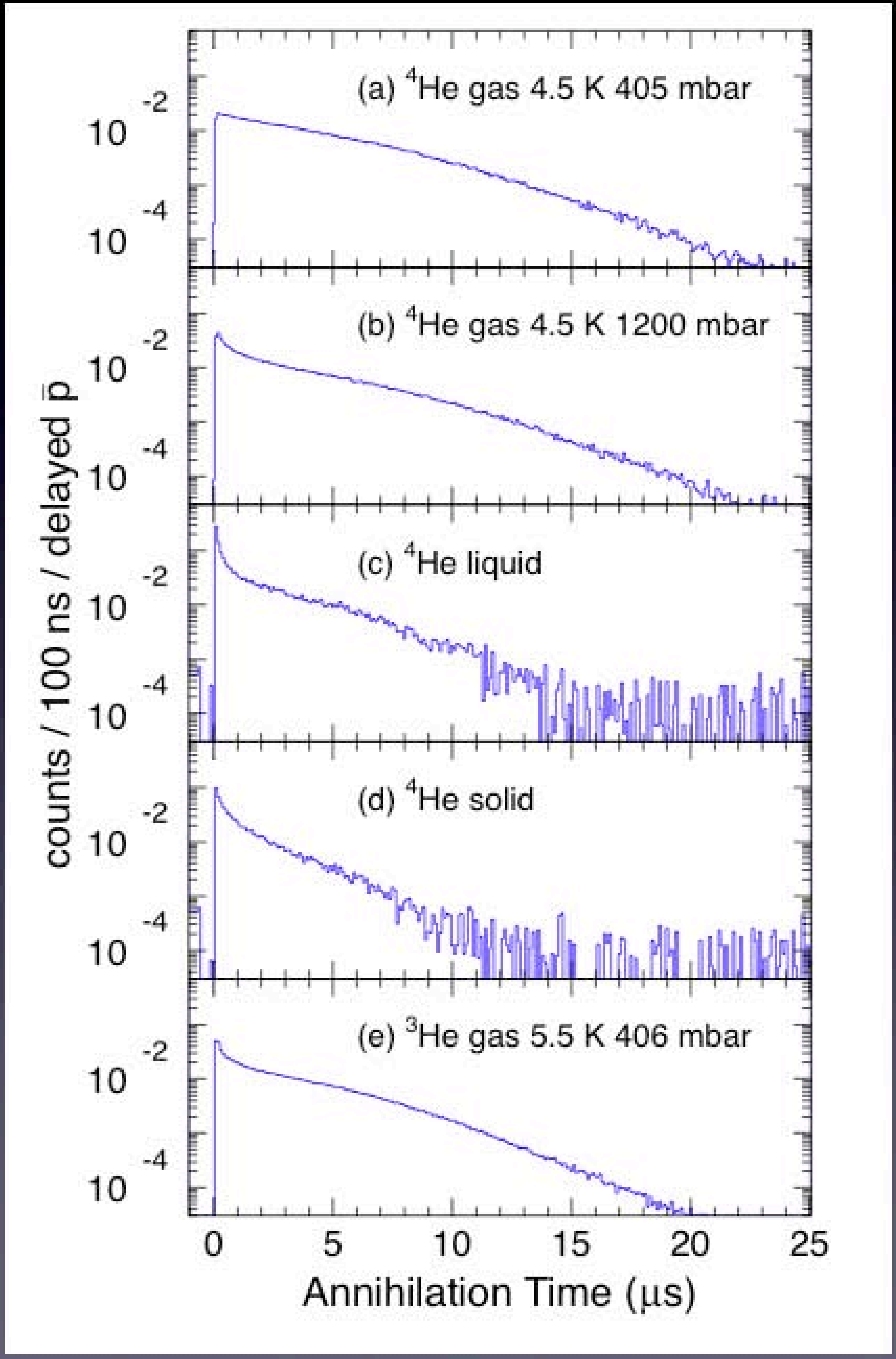
Iwasaki et al., PRL 67 (1991) 1246

Not just in liquid

Measurements continued at CERN LEAR

Established antiproton longevity in gas, liquid, solid helium-3 & helium-4

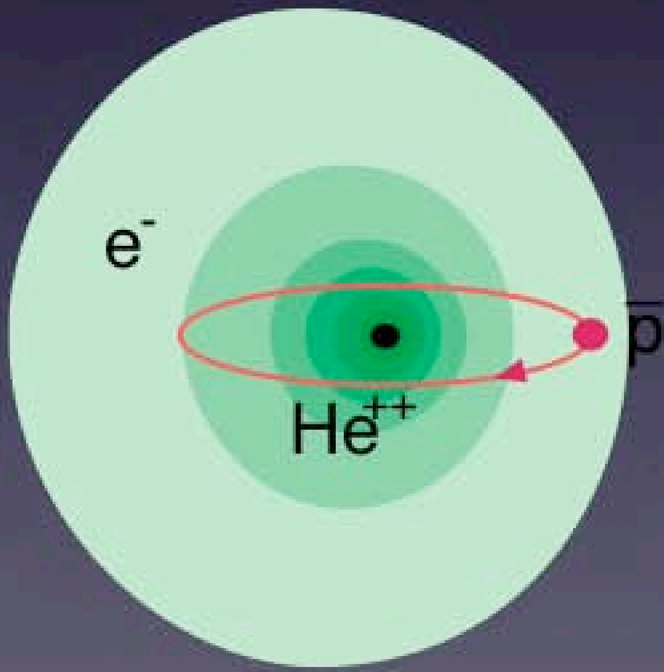
T. Yamazaki et al, 特別推進研究
@LEAR 1992-1996



antiprotonic helium

a naturally-occuring antiproton trap

electron is in ~ 1s (slightly polarized to the opposite side of $\bar{p}$)



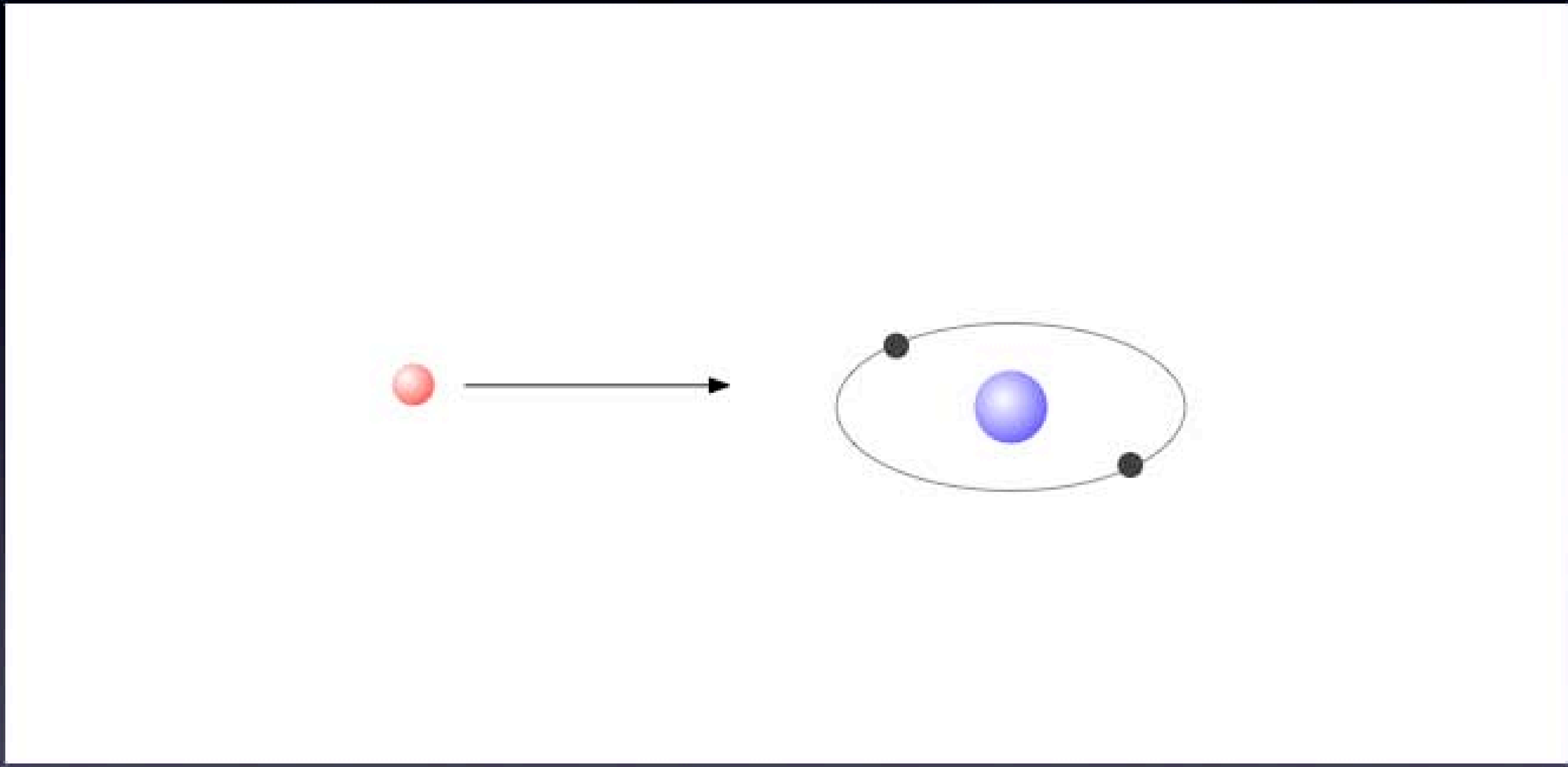
antiproton is in a highly excited (n~40) orbit

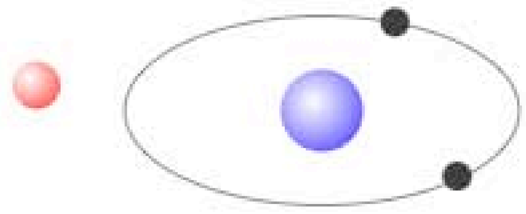
Easy production

Large yield

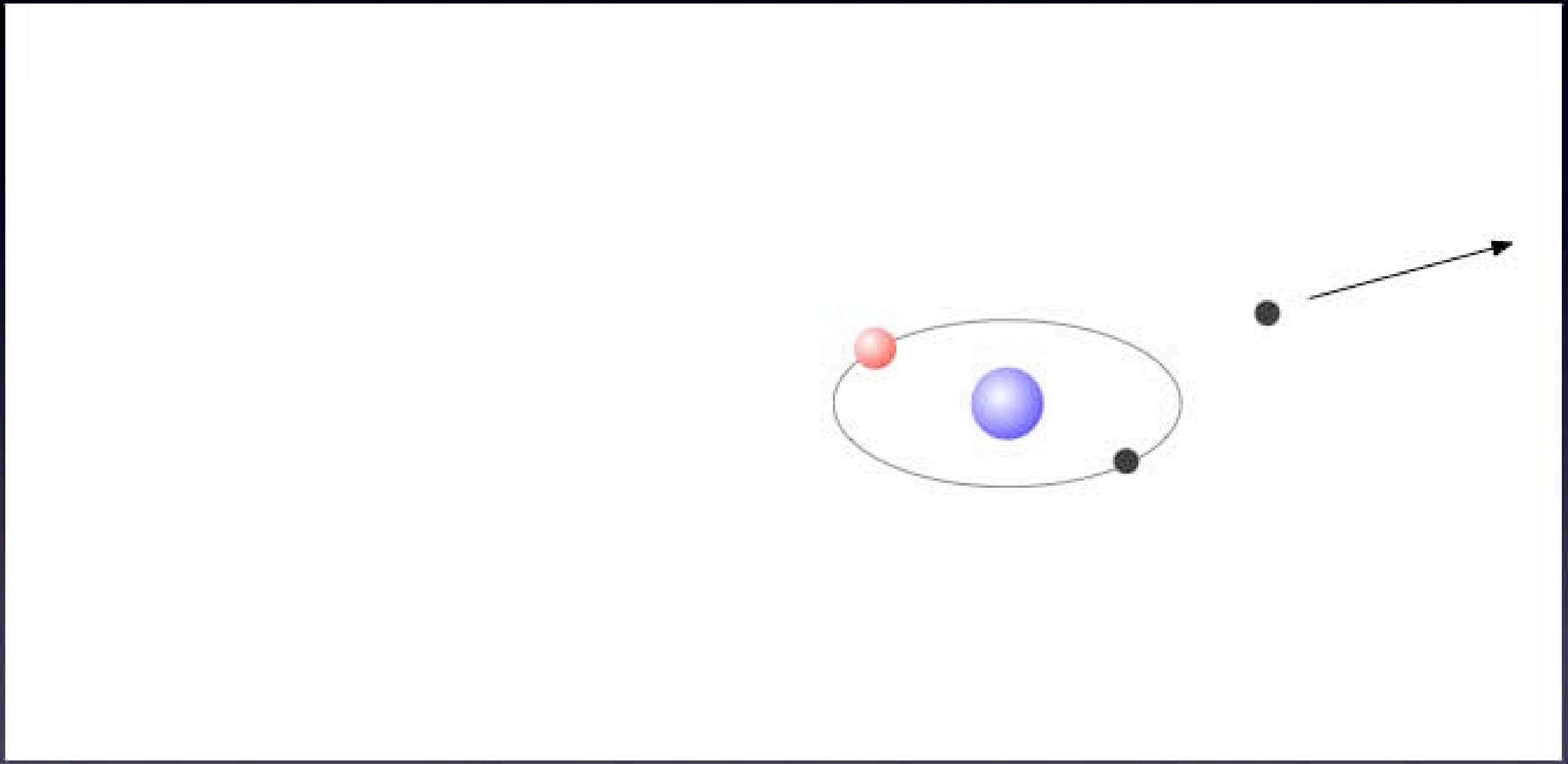
Long lifetime

Stop antiprotons in a low-temperature, dilute helium gas



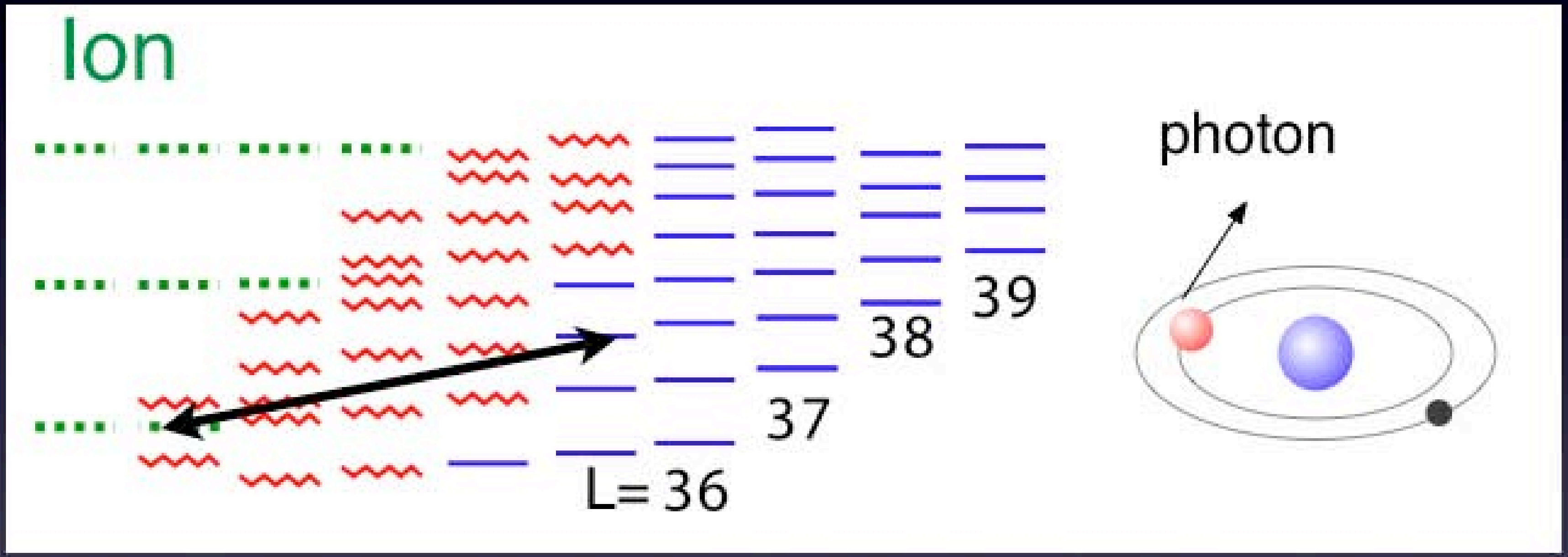


One of the two electrons of He, replaced by $\bar{p}$



3% of stopped antiprotons form $\bar{p}He$, lifetime > 3 μs

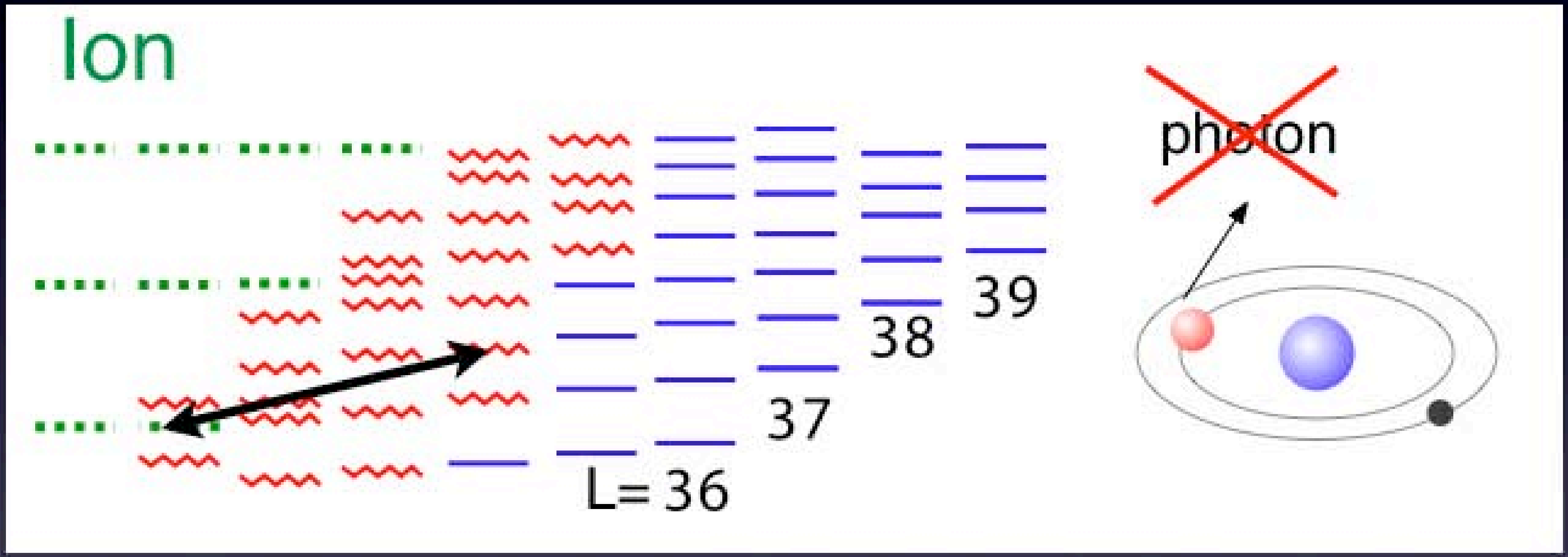
Mechanism of longevity



$\Delta L=4,\ \Gamma_{auger}<\Gamma_{radiative}$

If Auger is hindered (high multipolarity ΔL)
slow radiative deexcitation ($\sim \mu s$ / step)

Mechanism of longevity

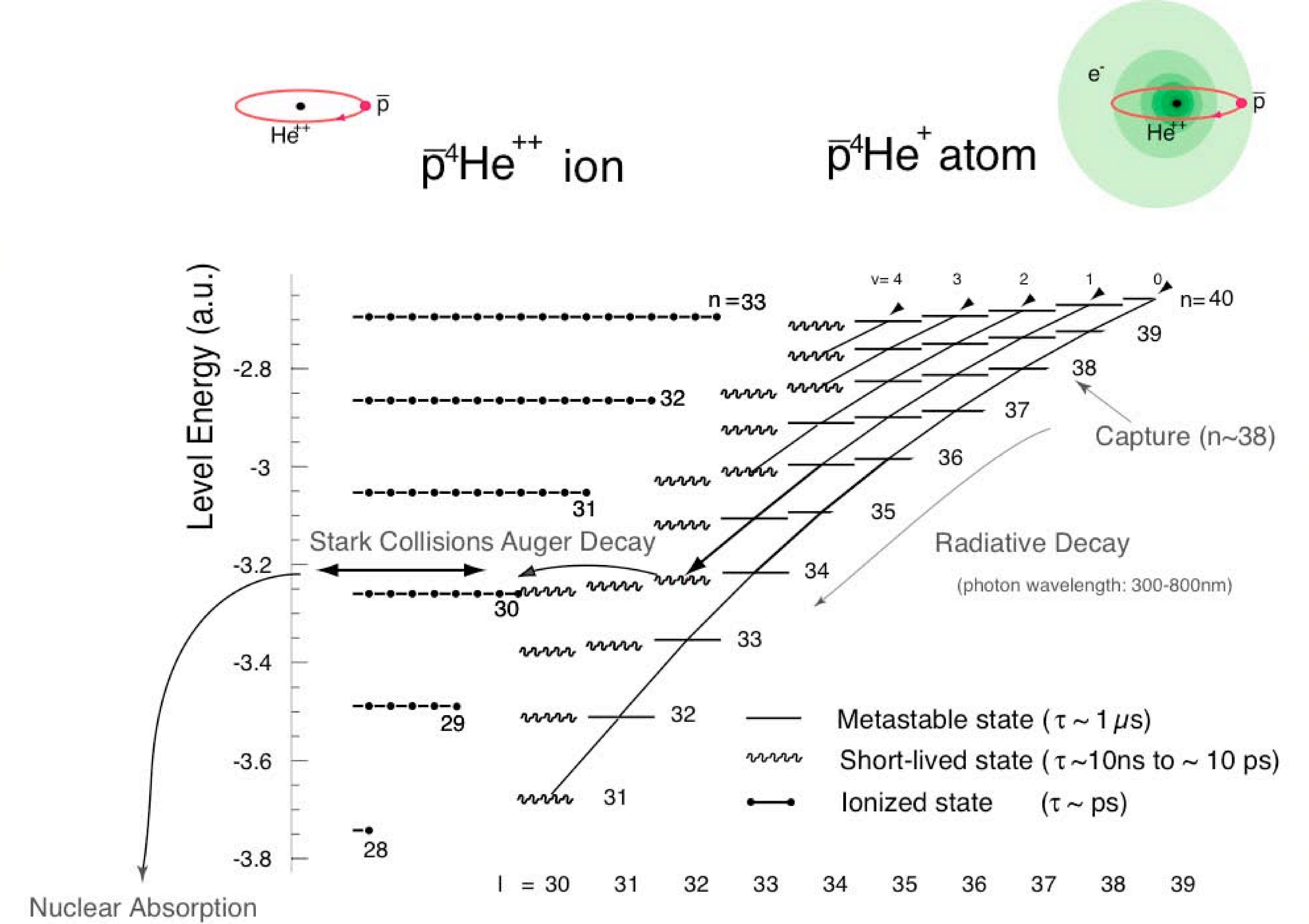


$\Delta L=3$, $\Gamma_{auger} > \Gamma_{radiative}$

If Auger is fast, the system is short lived

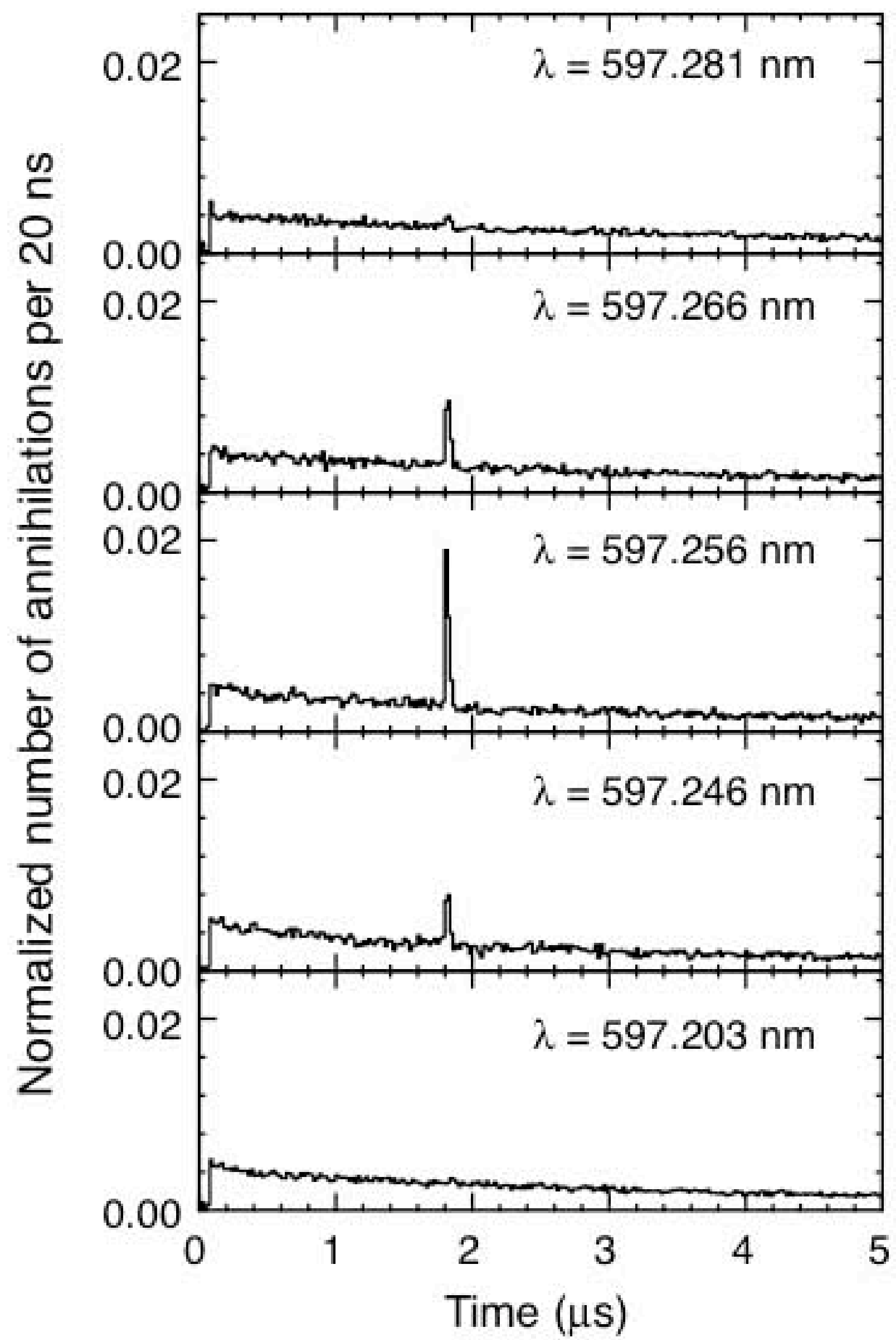
分光原理

laser-induced
annihilation



p̄ He++
p̄4He++ ion
p̄4He+ atom
e-
p̄ He++
Level Energy (a.u.)
-2.8
-3
-3.2
-3.4
-3.6
-3.8
n=33
32
31
30
29
28
v= 4
3
2
1
0
n= 40
39
38
37
36
35
34
33
32
31
Capture (n~38)
Stark Collisions Auger Decay
Radiative Decay
(photon wavelength: 300-800nm)
Metastable state (τ ~ 1 μs)
Short-lived state (τ ~10ns to ~ 10 ps)
Ionized state (τ ~ ps)
l = 30 31 32 33 34 35 36 37 38 39
Nuclear Absorption

An example, (n,l)=(39,35)→(38,34)



N. Morita et al, Phys. Rev. Lett. 72 (1994) 1180.

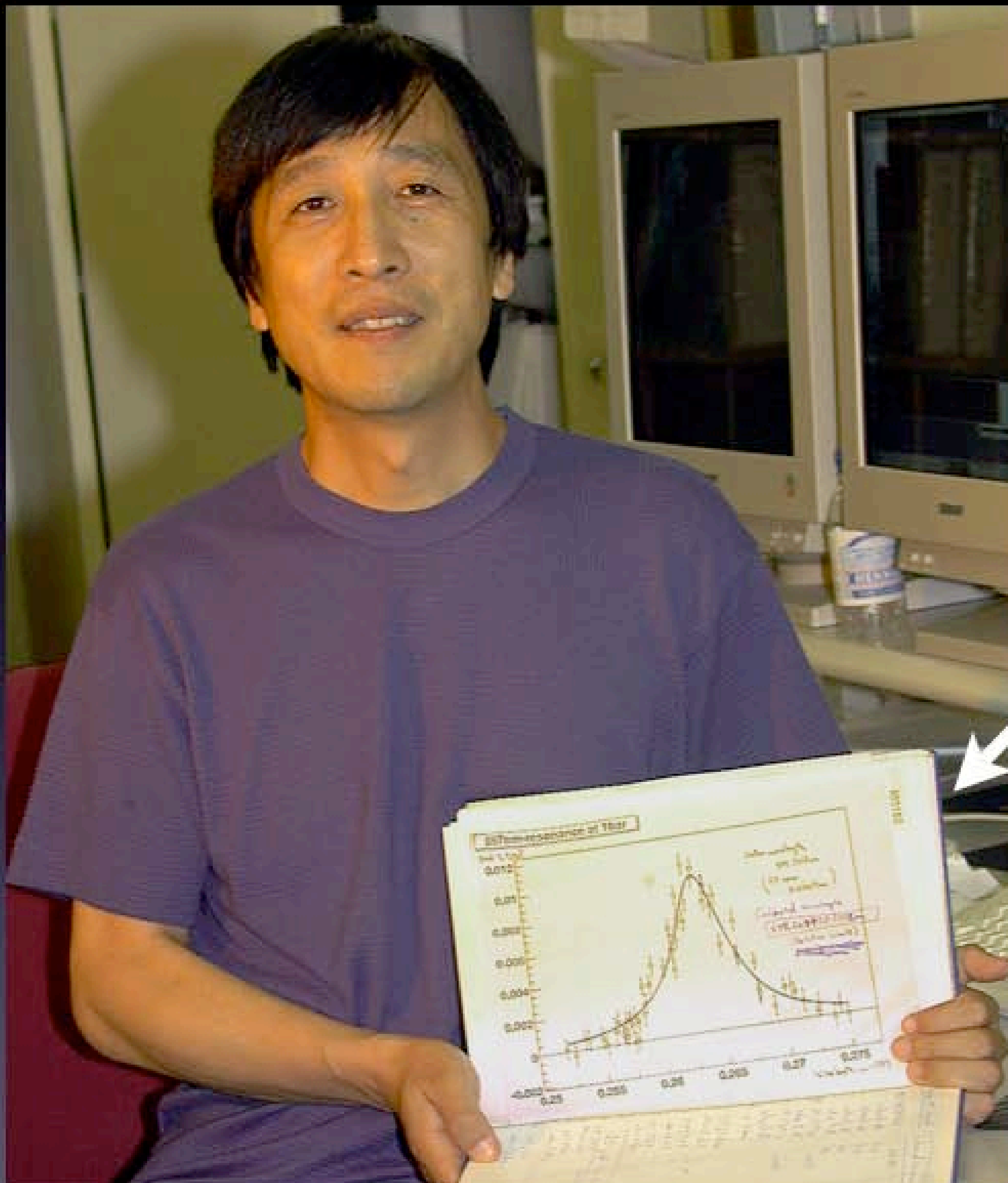


Photo CERN

レーザー共鳴を示す
グラフ
（共鳴強度 vs 周波数）

remember:

volume > cm^3

auger lifetime < 10 ns

↓

laser power density ~ MW/cm^2

パルスレーザー必須

also remember:

typical transition 10^{15} Hz

↓

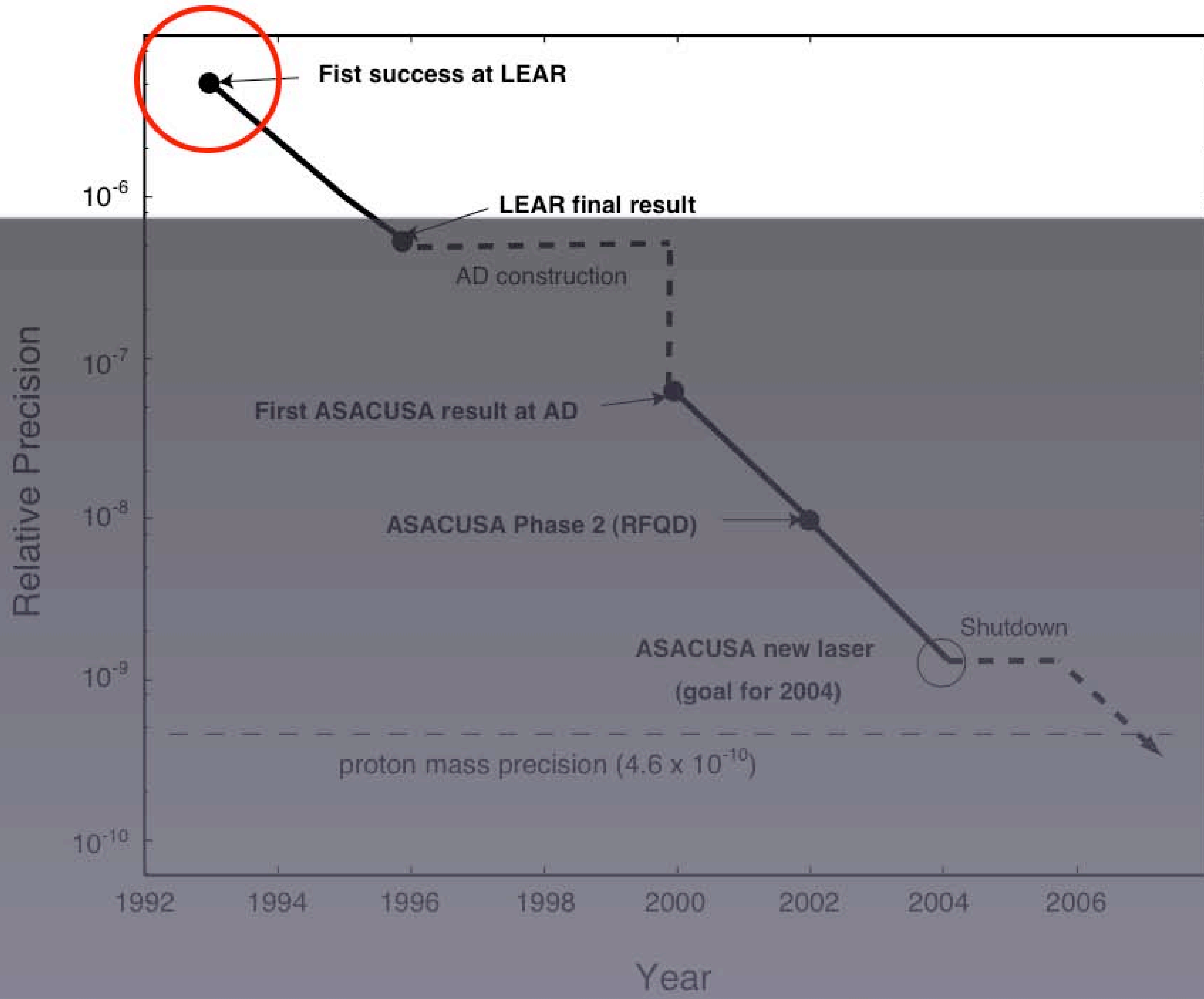
measurement precision of 1 MHz

↓

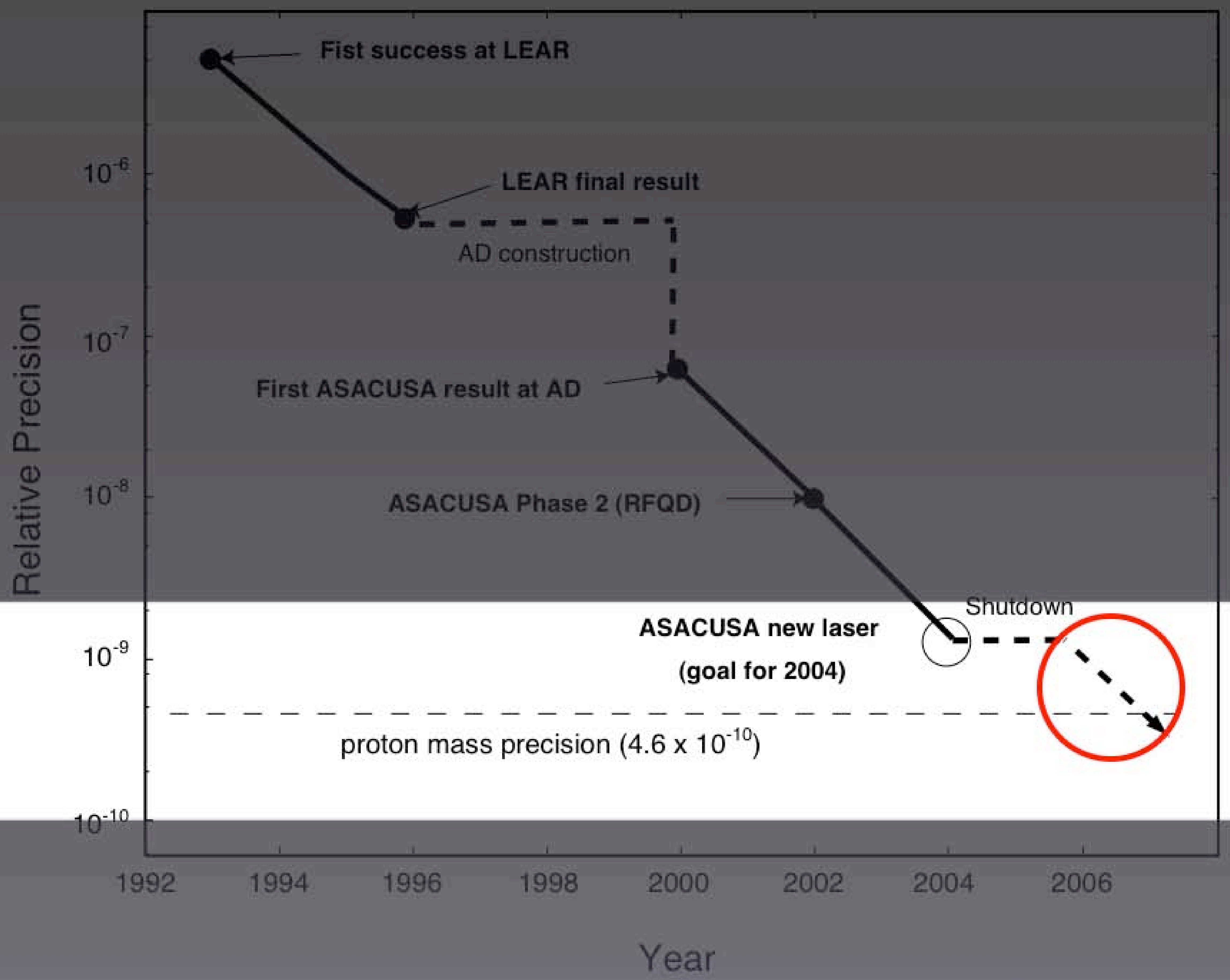
relative uncertainty 10^{-9} (ppb)

精度

reducing uncertainty



Fist success at LEAR
LEAR final result
AD construction
First ASACUSA result at AD
ASACUSA Phase 2 (RFQD)
Shutdown
ASACUSA new laser
(goal for 2004)
proton mass precision (4.6 x 10^-10)
Relative Precision
10^-6
10^-7
10^-8
10^-9
10^-10
1992
1994
1996
1998
2000
2002
2004
2006
Year



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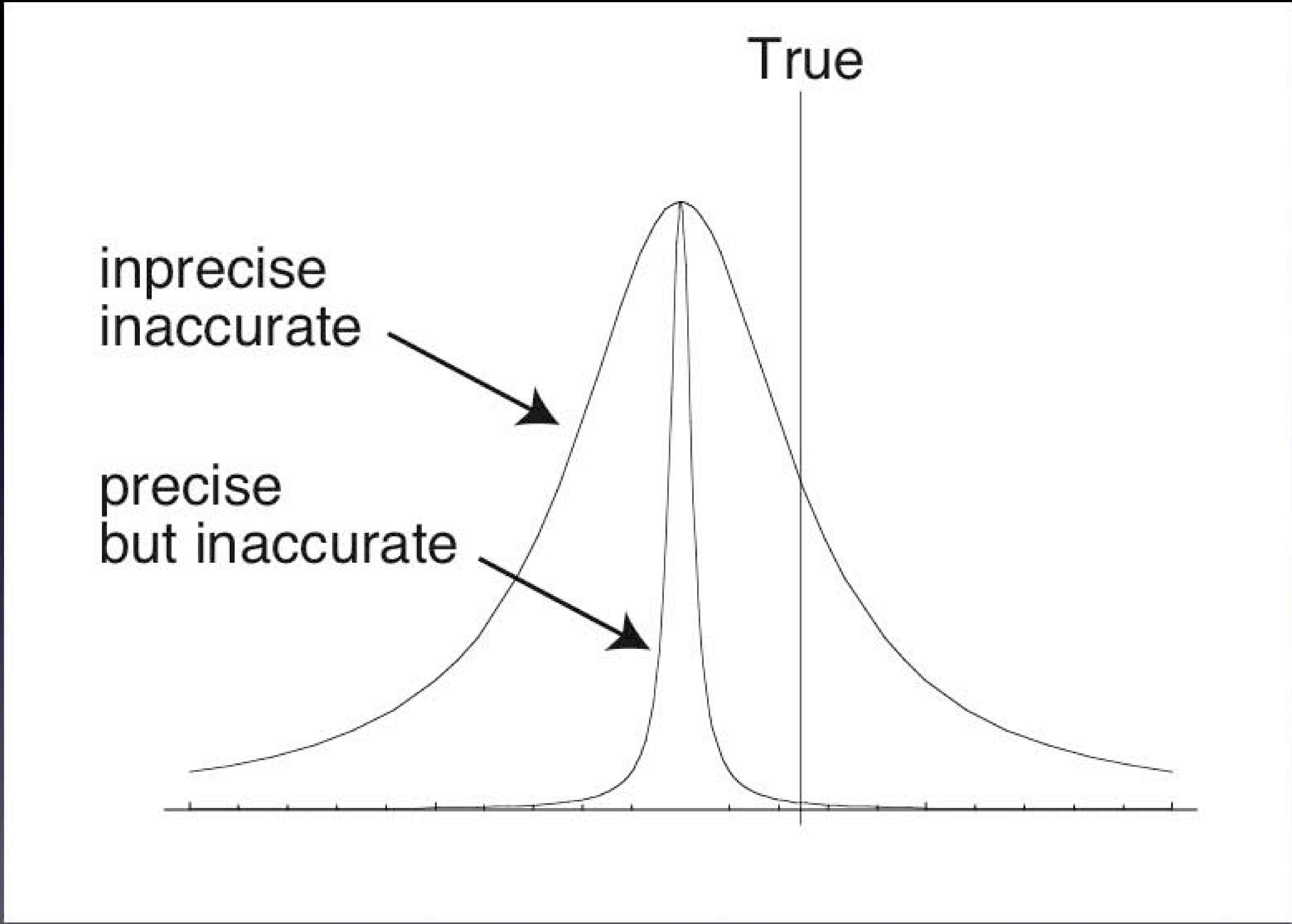
2006
Year

uncertaintyはどうやれば減るか

統計	ideally $\sigma = \frac{\text{line width}}{\sqrt{N}}$
線幅	
systematics	
systematics	
systematics	
systematics	
...	


True
inprecise
inaccurate
precise
but inaccurate

幅の要因	
自然幅	15MHz - 150kHz
Fourier幅	パルスレーザー パルス長
衝突	RFQD
ドップラー幅	2光子分光
レーザー単色性	パルスレーザー →CWレーザー

シフトの要因	
衝突	RFQD
チャープ	~2MHz, パルスレーザー不可避
周波数較正	光周波数comb
AC Stark shift	∝ Power
(理論)	~MHz?

反陽子減速器

CERN AD

(Antiproton Decelerator)

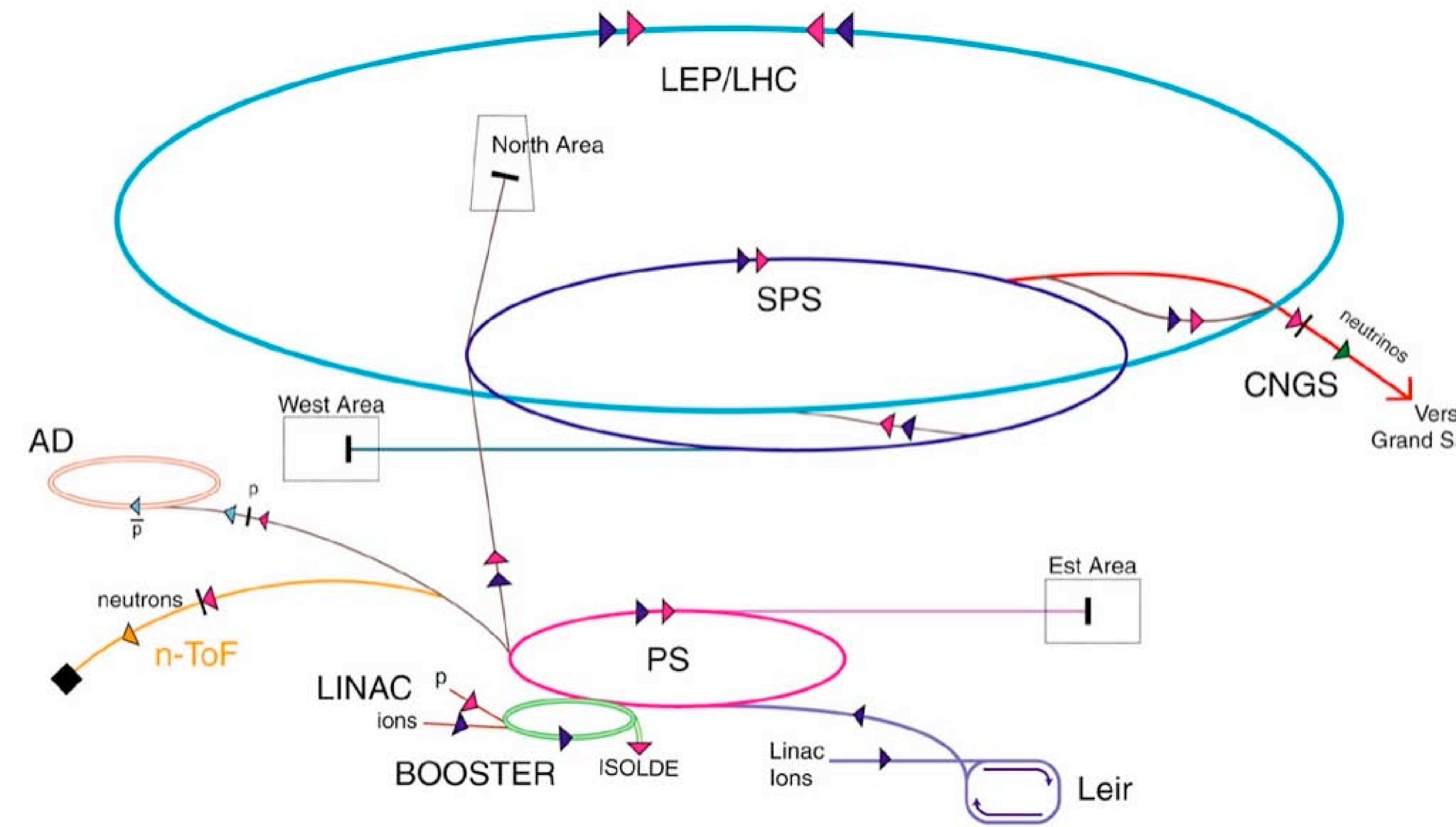
and ASACUSA RFQD

(radio-frequency quadrupole decelerator)

ASACUSA

atomic spectroscopy
and
collisions using
slow antiprotons

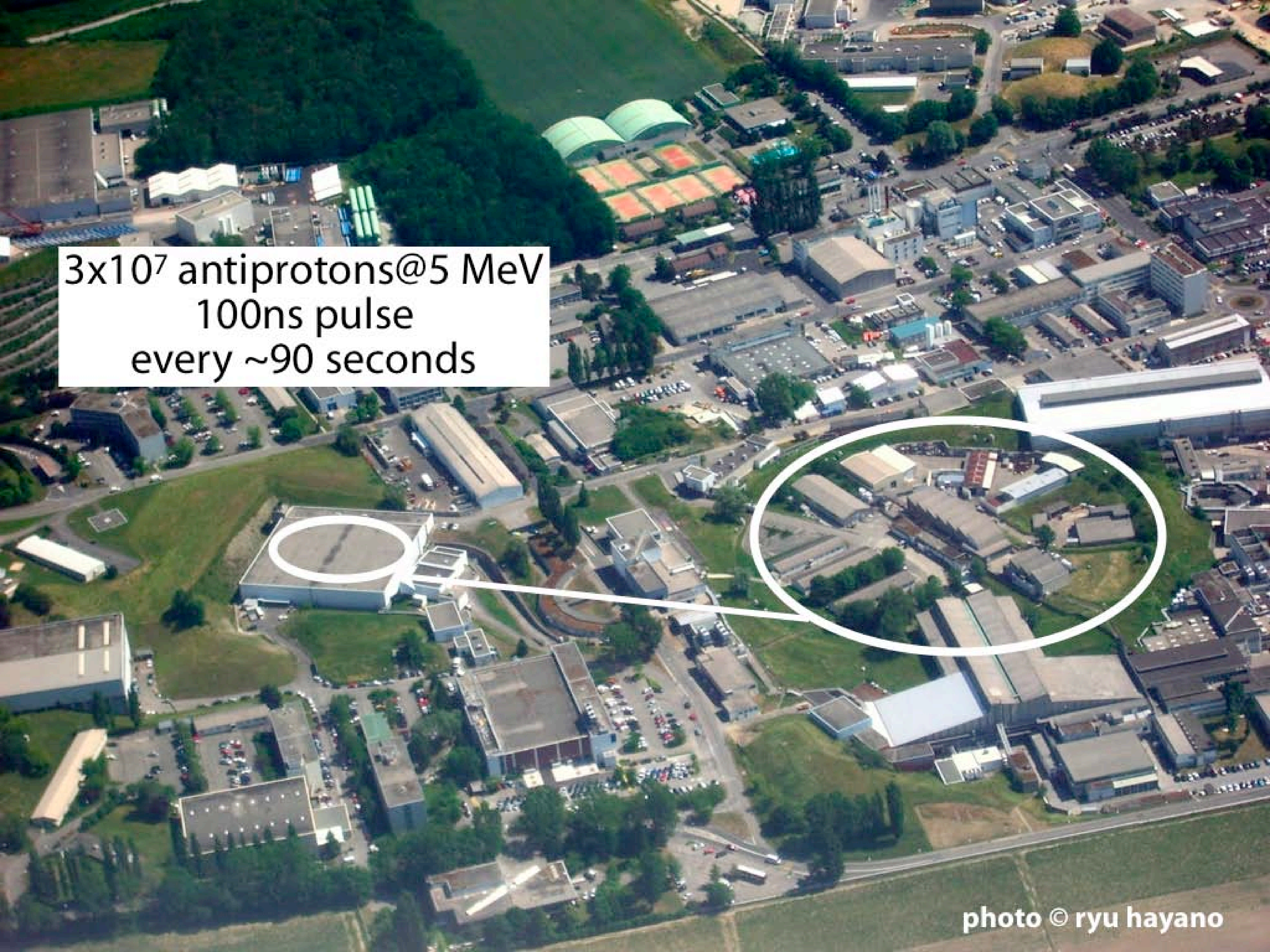
Accelerator chain of CERN (operating or approved projects)



p (proton)
ion
neutrons
p̄ (antiproton)
proton/antiproton conversion
neutrinos

AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron

LHC Large Hadron Collider
n-ToF Neutrons Time of Flight
CNGS Cern Neutrinos Grand Sasso



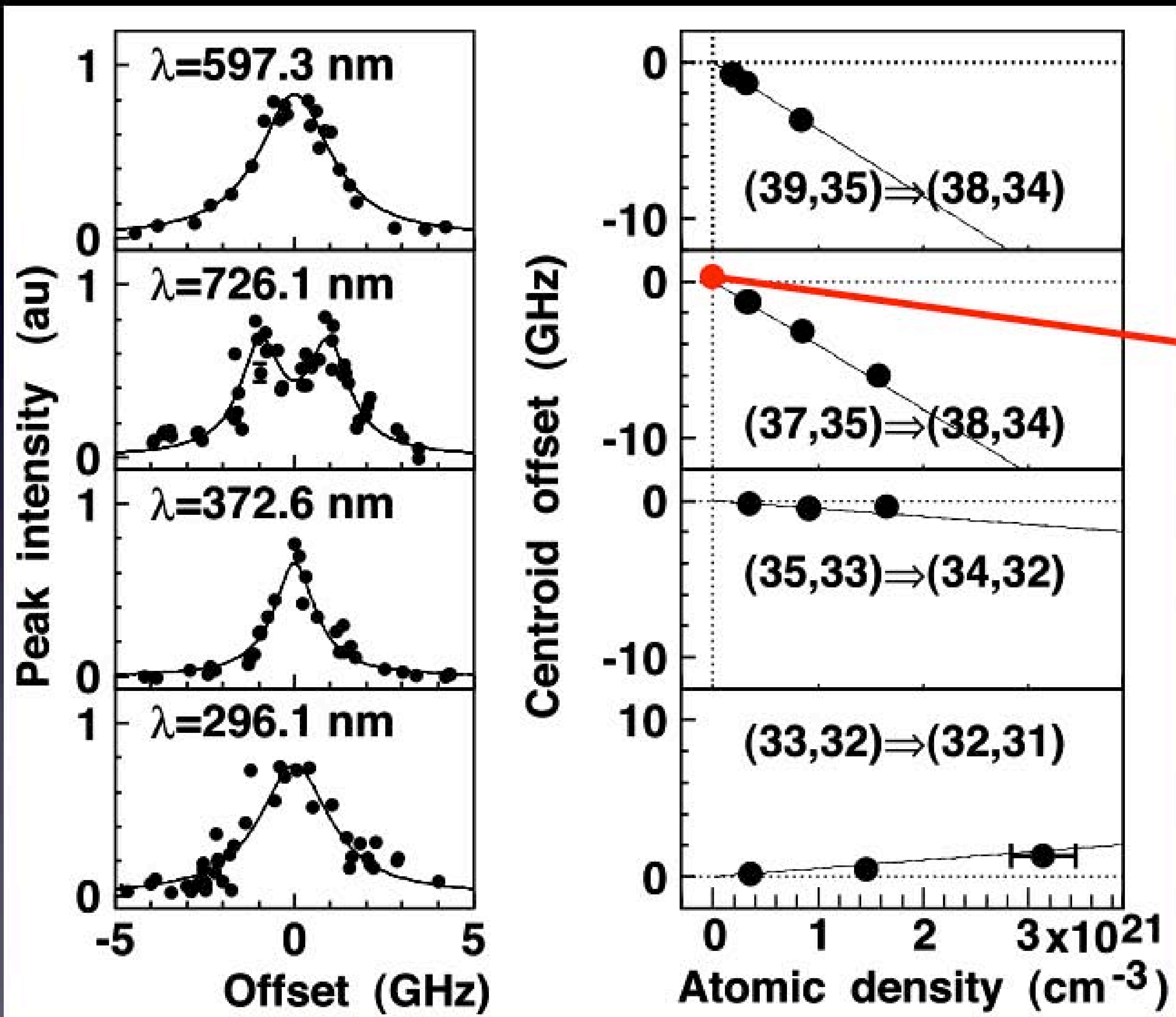
3x10⁷ antiprotons@5 MeV
100ns pulse
every ~90 seconds
photo © ryu hayano

初

the first result @ AD

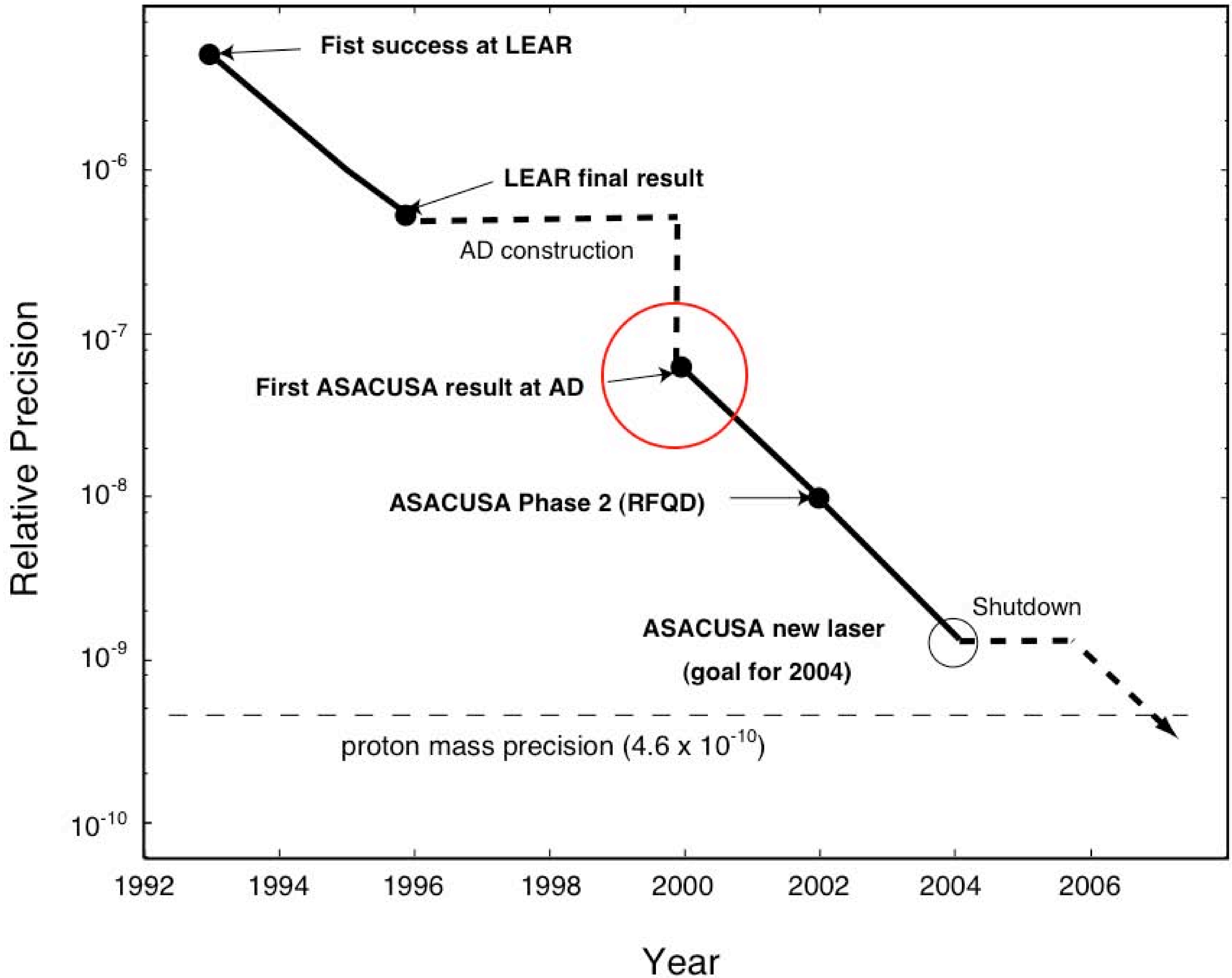
M. Hori etal., Phys. Rev. Lett. 87, 093401(2001).

Collisional frequency shift correction



Antiprotons stopped in a dense (~1bar, ~5K) helium gas target

zero-density extrapolation needed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衝突

reducing collision

M. Hori et al., Phys. Rev. Lett. 91, 123401(2003).

幅の要因	
自然幅	15MHz - 150kHz
Fourier幅	パルスレーザー パルス長
衝突	RFQD
ドップラー幅	2光子分光
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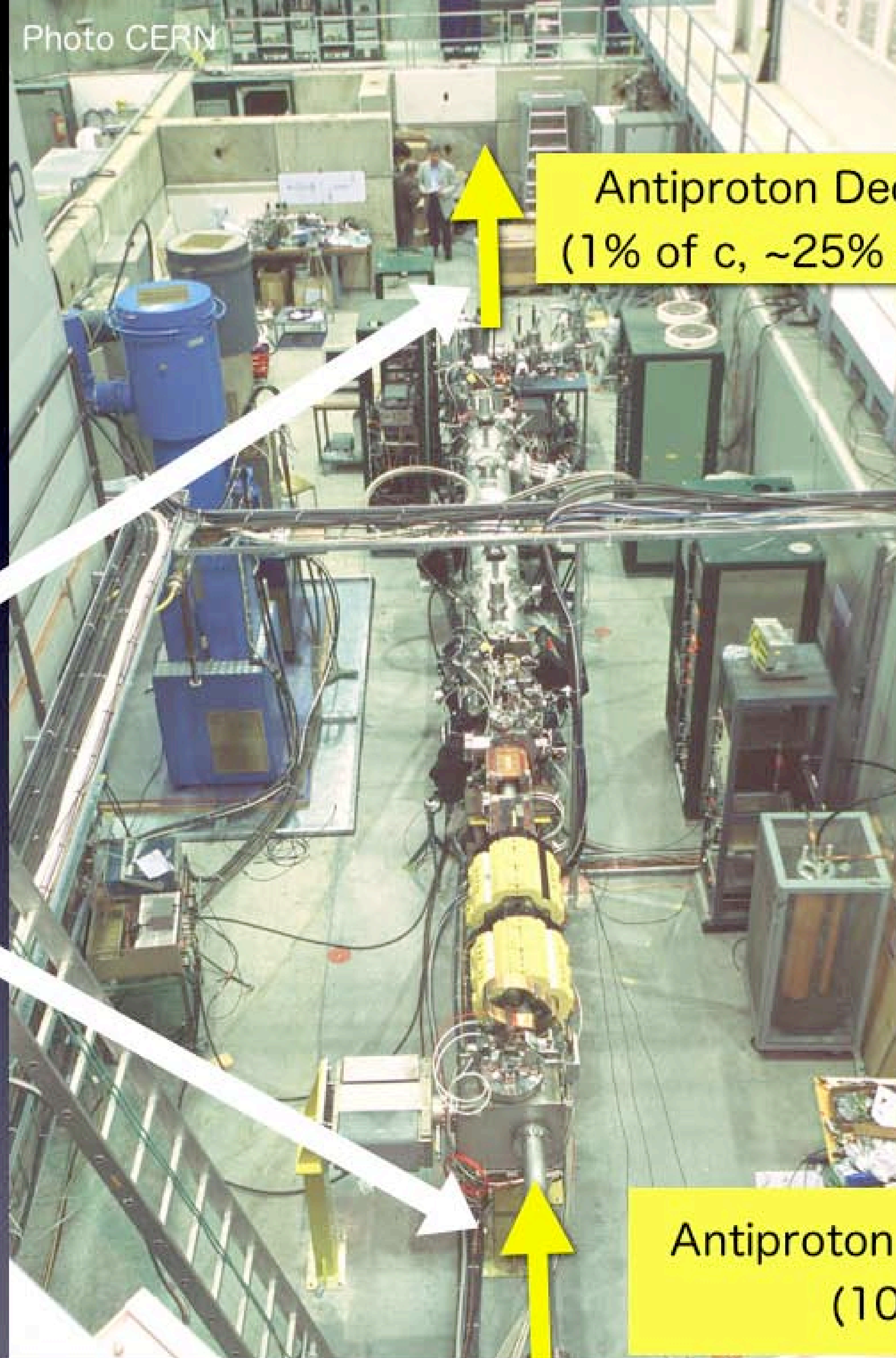
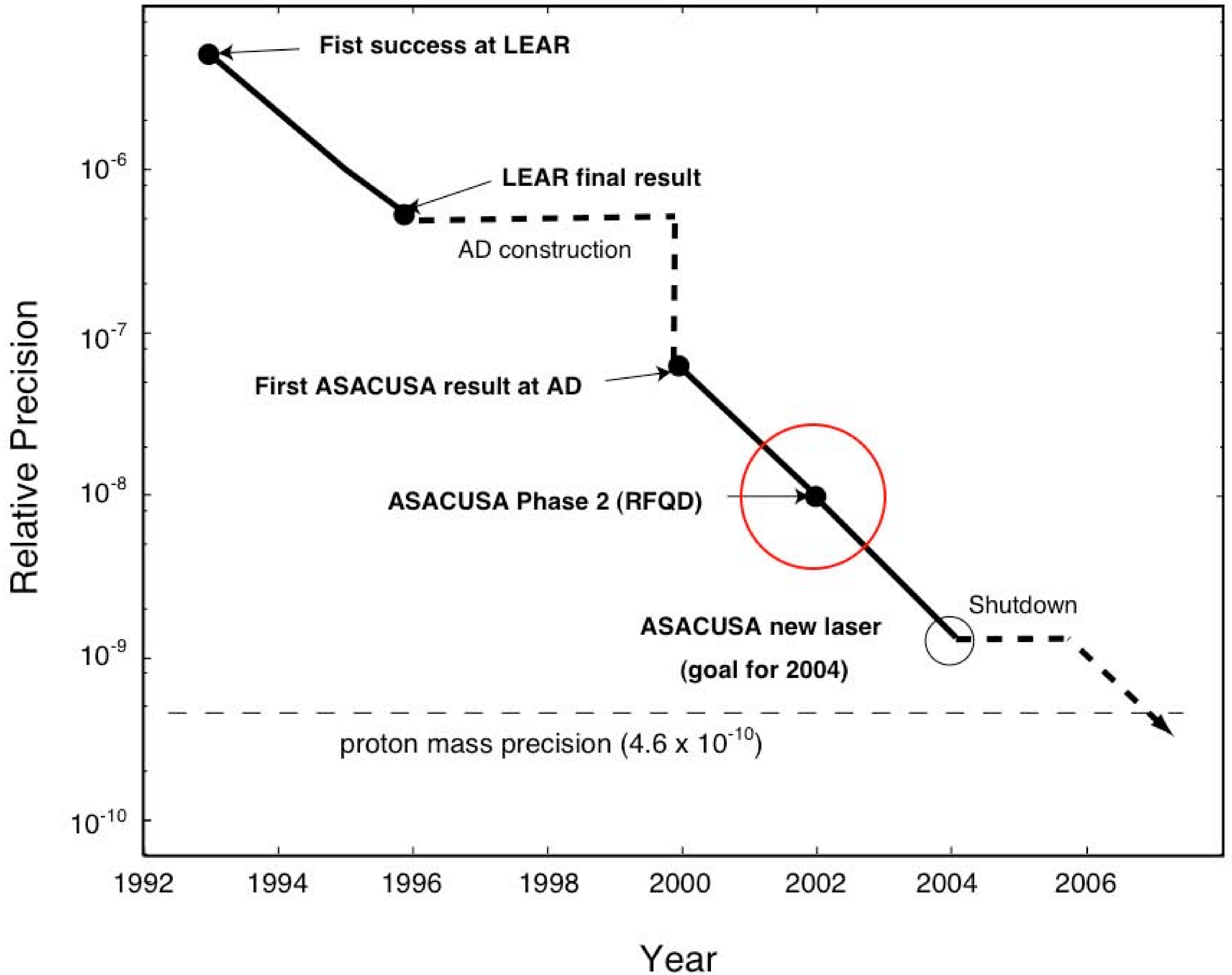
衝突	RFQD
チャープ	~2MHz, パルスレーザー不可避
周波数較正	光周波数comb
AC Stark	∝ Power
(理論)	~MHz?

small (a few MHz)
collisional shift and width
(which we correct)

Typical target density
10^{16}-10^{18} cm^{-3}
10^{21} cm^{-3}





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Year

単色

better laser

M. Hori et al., Phys. Rev. Lett. 96, 243401(2006)

幅の要因	
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周波数較正	光周波数comb
AC Stark	∝ Power
(理論)	~MHz?

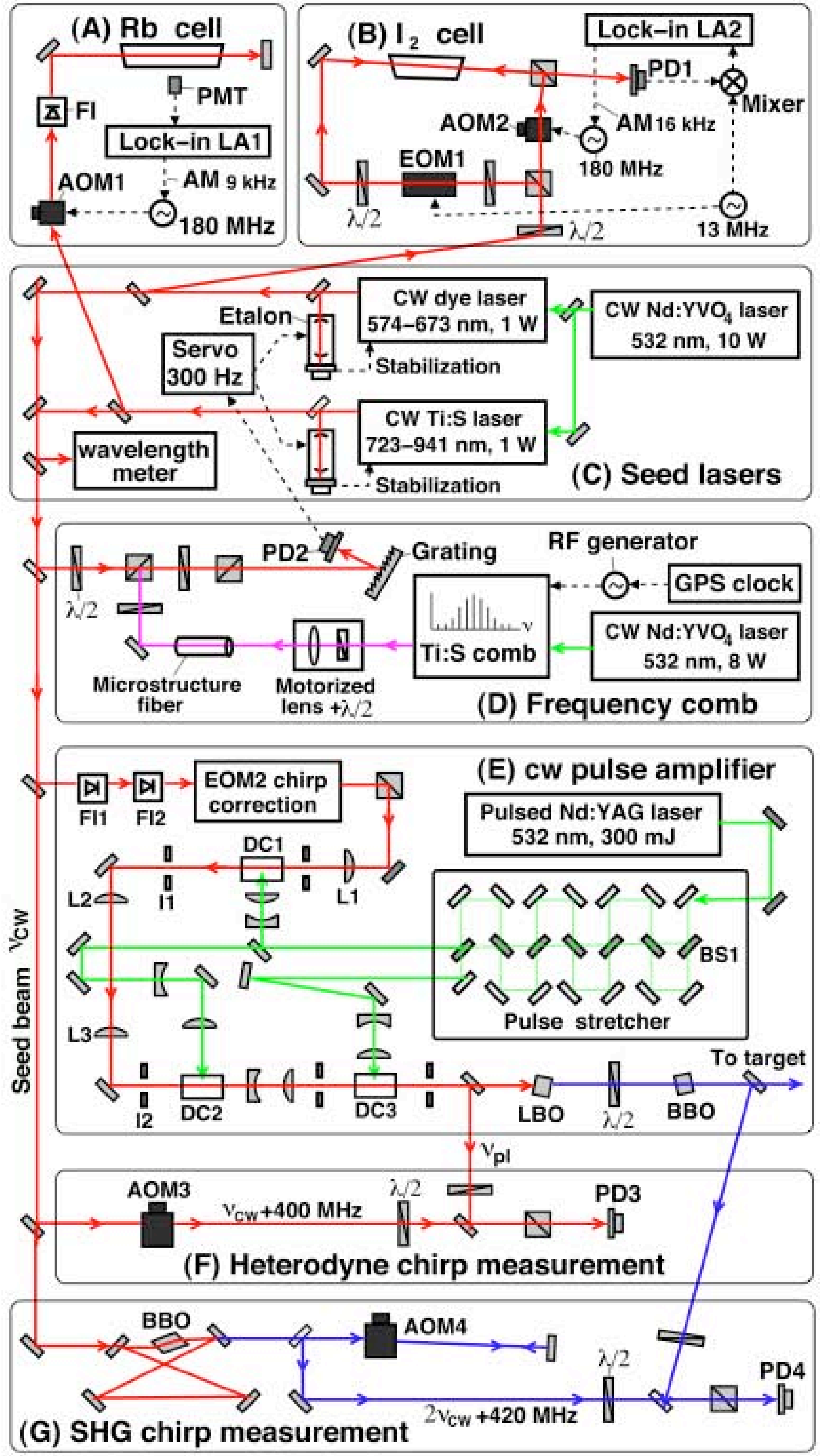
Known lines

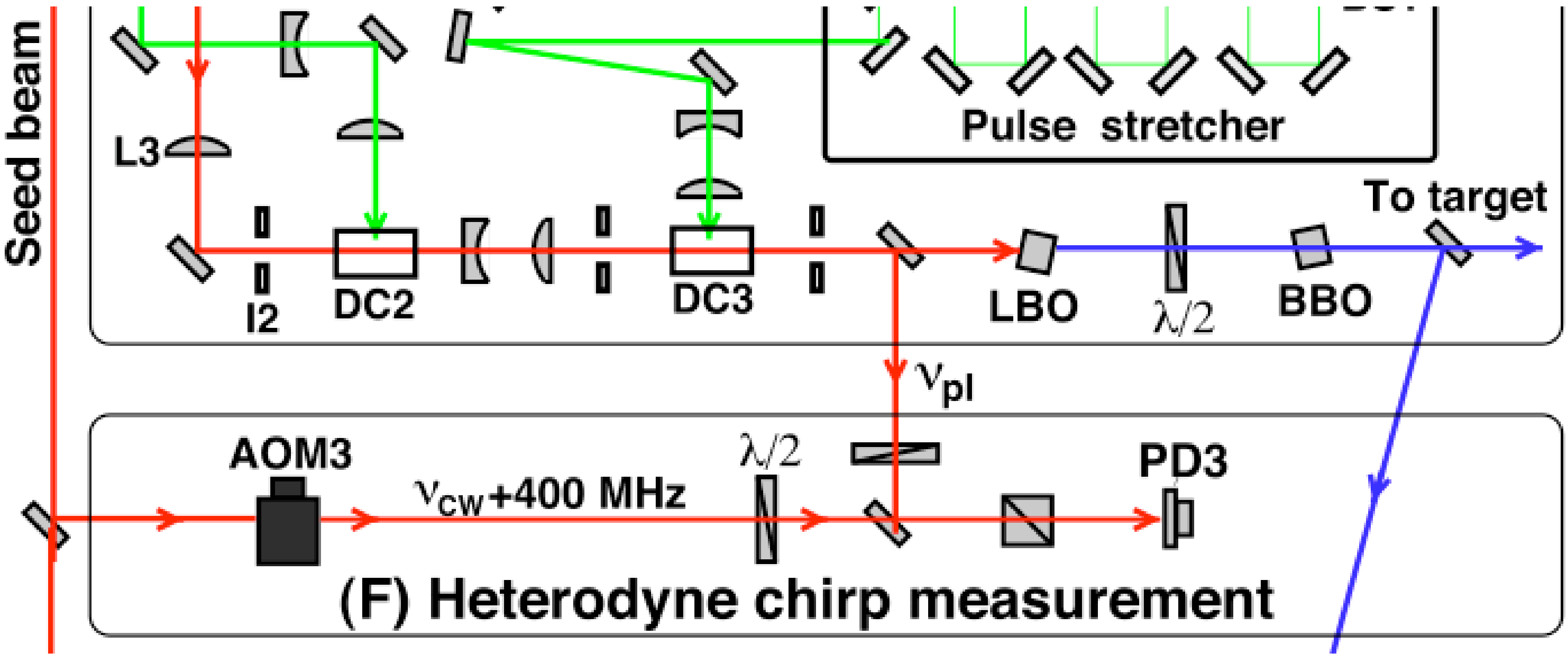
CW

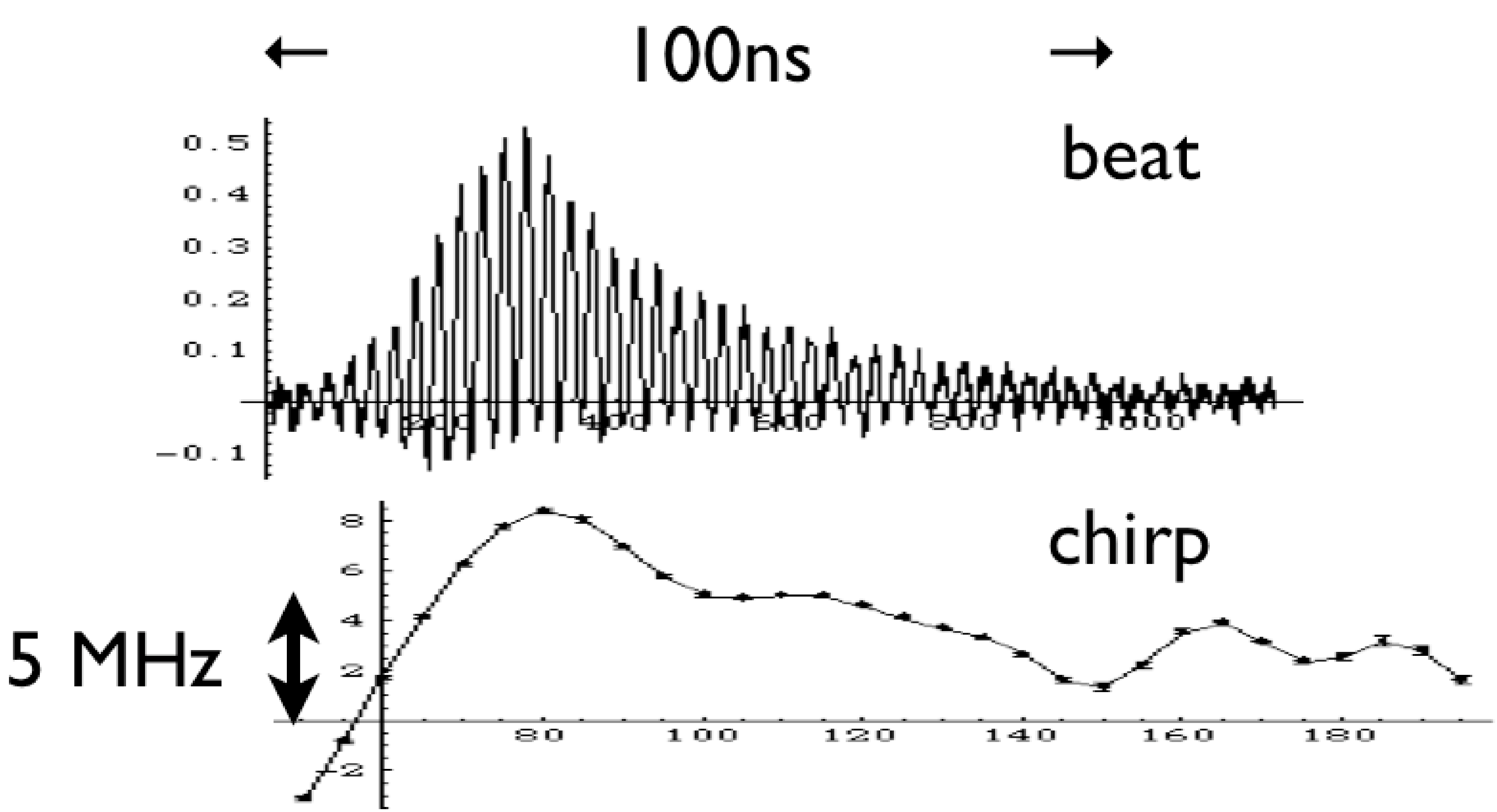
Comb

Amplifier stretcher

Chirp



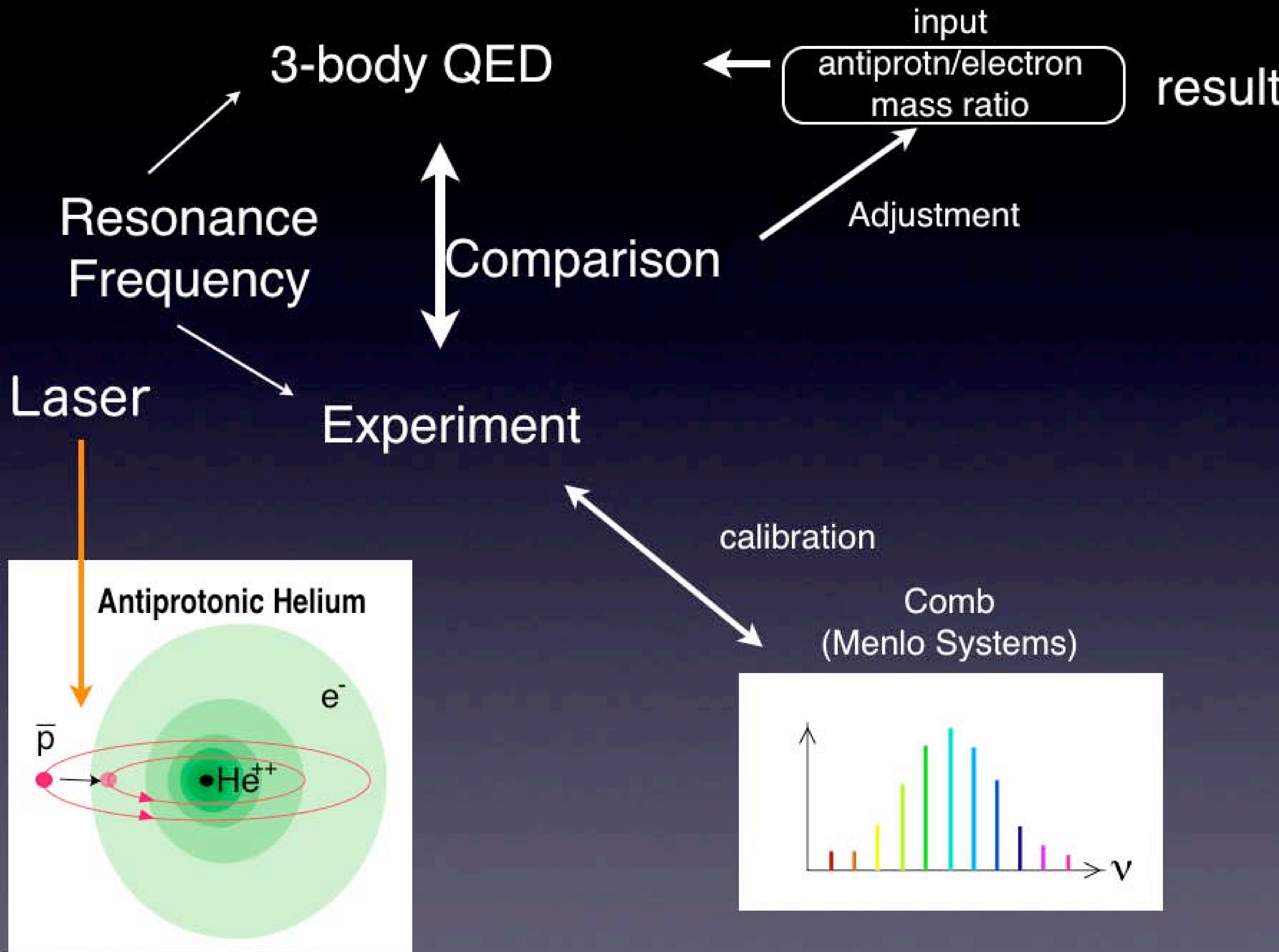

Seed beam
L3
I2
DC2
DC3
Pulse stretcher
To target
LBO
λ/2
BBO
ν_pl
AOM3
ν_cw+400 MHz
λ/2
PD3
(F) Heterodyne chirp measurement


100ns
beat
0.5
0.4
0.3
0.2
0.1
−0.1
chirp
5 MHz
8
6
4
2
-2
80
100
120
140
160
180

質量比

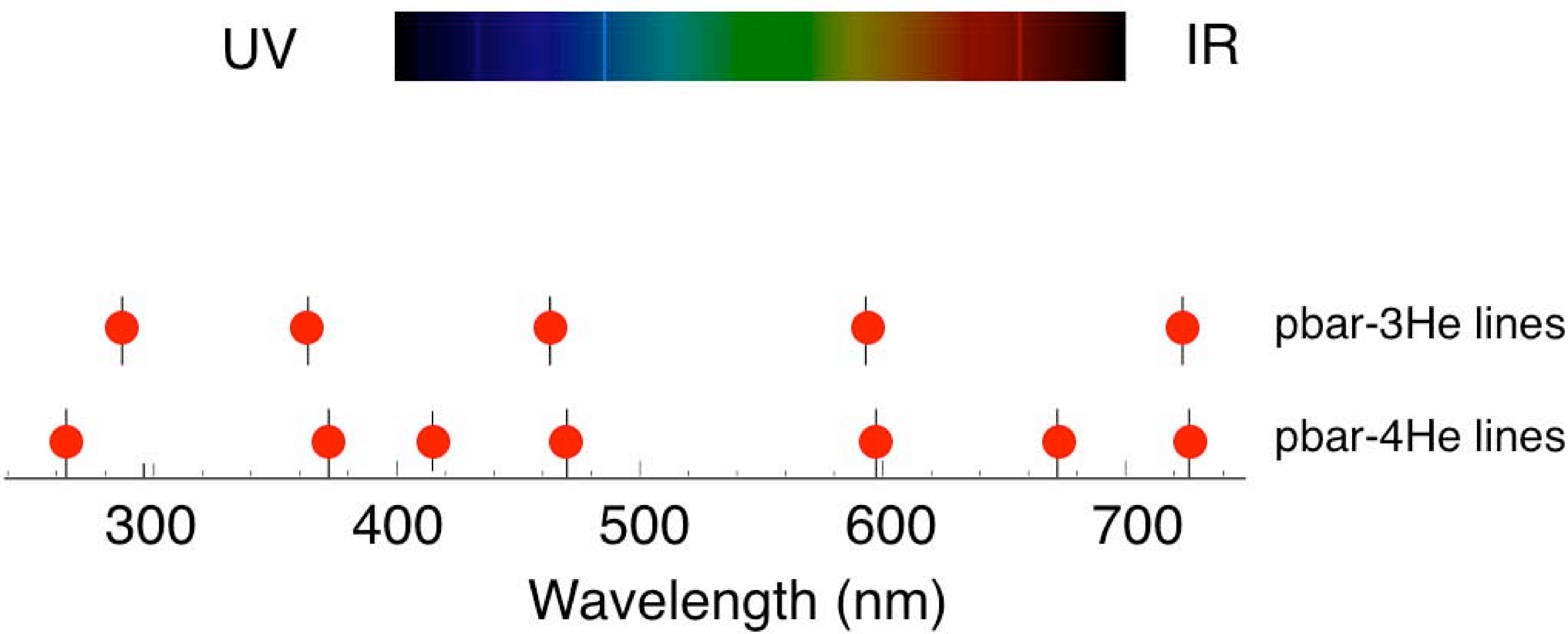
How to obtain

$m_{\bar{p}}/m_e$

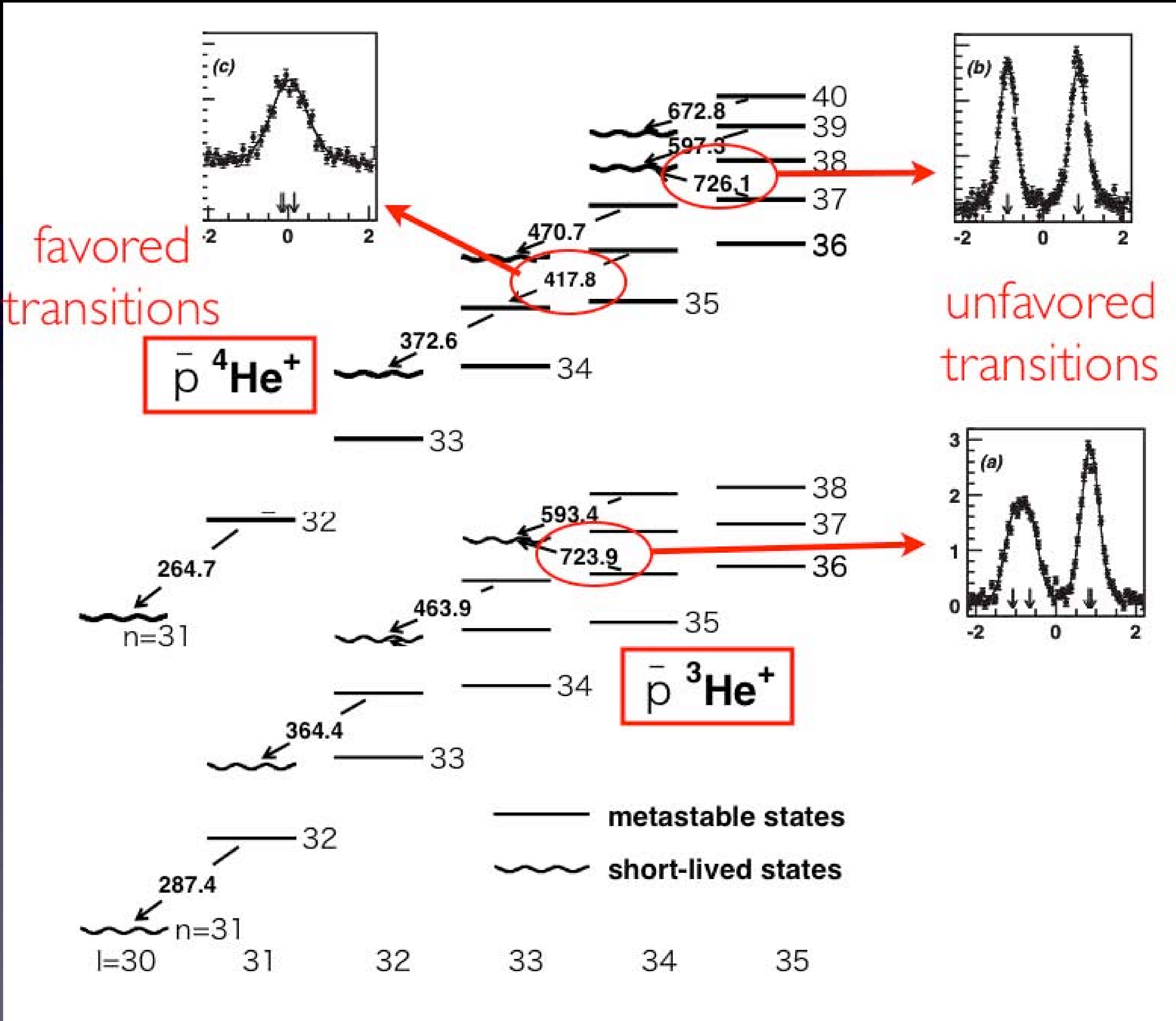


3-body QED
input
antiprotn/electron
mass ratio
result
Resonance
Frequency
Comparison
Adjustment
Laser
Experiment
calibration
Antiprotonic Helium
e-
p̄
He++
Comb
(Menlo Systems)
ν

wavelengths of the resonance lines



12 transitions were measured



理論

and the results were compared with

(spinless) 3-body QED theoretical calculations

Theory - non-relativistic H

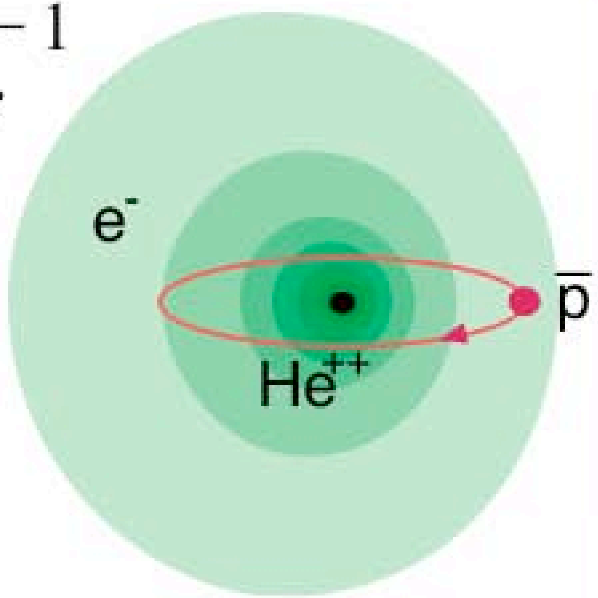
antiproton

electron

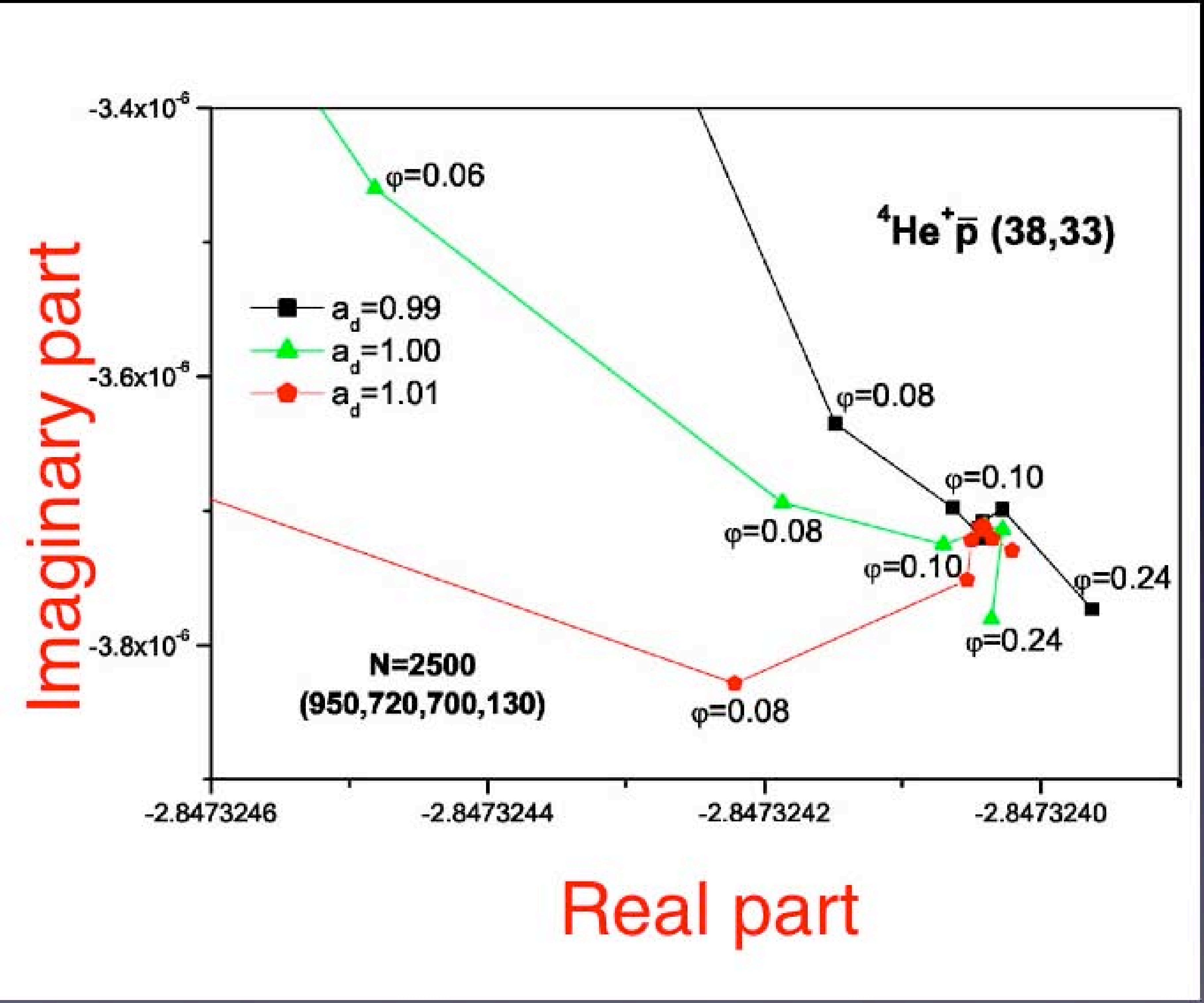
$$H = T + V$$

$$= -\frac{1}{2\mu_1}\nabla_{\mathbf{R}}^2 - \frac{1}{2\mu_2}\nabla_{\mathbf{r}}^2 - \frac{1}{M_{\mathrm{He}}}\nabla_{\mathbf{R}} \cdot \nabla_{\mathbf{r}} - \frac{2}{R} - \frac{2}{r} + \frac{1}{|\mathbf{R} - \mathbf{r}|},$$

$$\mu_1^{-1} = M_{\mathrm{He}}^{-1} + M_X^{-1}, \quad \mu_2^{-1} = M_{\mathrm{He}}^{-1} + m_e^{-1}$$



Complex coordinate rotation (CCR) method



Not true bound states

Careful treatment of Auger decay is needed

CCR calculates complex eigen values

Korobov

add relativistic correction (~100 ppm)

$$
\begin{aligned}
H &= T + V \\
&= -\frac{1}{2\mu_1}\nabla_{\mathbf{R}}^2 - \frac{1}{2\mu_2}\nabla_{\mathbf{r}}^2 - \frac{1}{M_{\mathrm{He}}}\nabla_{\mathbf{R}}\cdot\nabla_{\mathbf{r}} - \frac{2}{R} - \frac{2}{r} + \frac{1}{|\mathbf{R}-\mathbf{r}|},
\end{aligned}
$$

$$\mu_1^{-1} = M_{\mathrm{He}}^{-1} + M_X^{-1}, \quad \mu_2^{-1} = M_{\mathrm{He}}^{-1} + m_e^{-1},$$

$$E_{rc} = \alpha^2 \left\langle -\frac{\mathbf{p}_e^4}{8m_e^3} + \frac{4\pi}{8m_e^2}\left[Z_{\mathrm{He}}\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}\delta(\mathbf{r}_{\bar{p}})\right] \right\rangle .$$

add self energy (~15 ppm)

$$H = T + V$$

$$= -\frac{1}{2\mu_1}\nabla_{\mathbf{R}}^2 - \frac{1}{2\mu_2}\nabla_{\mathbf{r}}^2 - \frac{1}{M_{\mathrm{He}}}\nabla_{\mathbf{R}}\cdot\nabla_{\mathbf{r}} - \frac{2}{R} - \frac{2}{r} + \frac{1}{|\mathbf{R}-\mathbf{r}|},$$

$$\mu_1^{-1} = M_{\mathrm{He}}^{-1} + M_X^{-1}, \quad \mu_2^{-1} = M_{\mathrm{He}}^{-1} + m_e^{-1},$$

$$E_{rc} = \alpha^2 \left\langle -\frac{\mathbf{p}_e^4}{8m_e^3} + \frac{4\pi}{8m_e^2}[Z_{\mathrm{He}}\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}\delta(\mathbf{r}_{\bar{p}})] \right\rangle.$$

Bethe logarithm

$$E_{se} = \frac{4\alpha^3}{3m_e^2}\left[\ln\frac{1}{\alpha^2} - \ln\frac{k_0}{R_\infty} + \frac{5}{6} - \frac{3}{8}\right]\langle Z_{\mathrm{He}}\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}\delta(\mathbf{r}_{\bar{p}})\rangle$$

$$+ \frac{4\alpha^4}{3m_e^2}\left[3\pi\left(\frac{139}{128} - \frac{1}{2}\ln 2\right)\right]\langle Z_{\mathrm{He}}^2\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}^2\delta(\mathbf{r}_{\bar{p}})\rangle$$

$$- \frac{4\alpha^5}{3m_e^2}\left[\frac{3}{4}\right]\langle Z_{\mathrm{He}}^3 \ln^2(Z_{\mathrm{He}}\alpha)^{-2}\delta(\mathbf{r}_{\mathrm{He}})$$

$$+ Z_{\bar{p}}^3 \ln^2(Z_{\bar{p}}\alpha)^{-2}\delta(\mathbf{r}_{\bar{p}})\rangle,$$

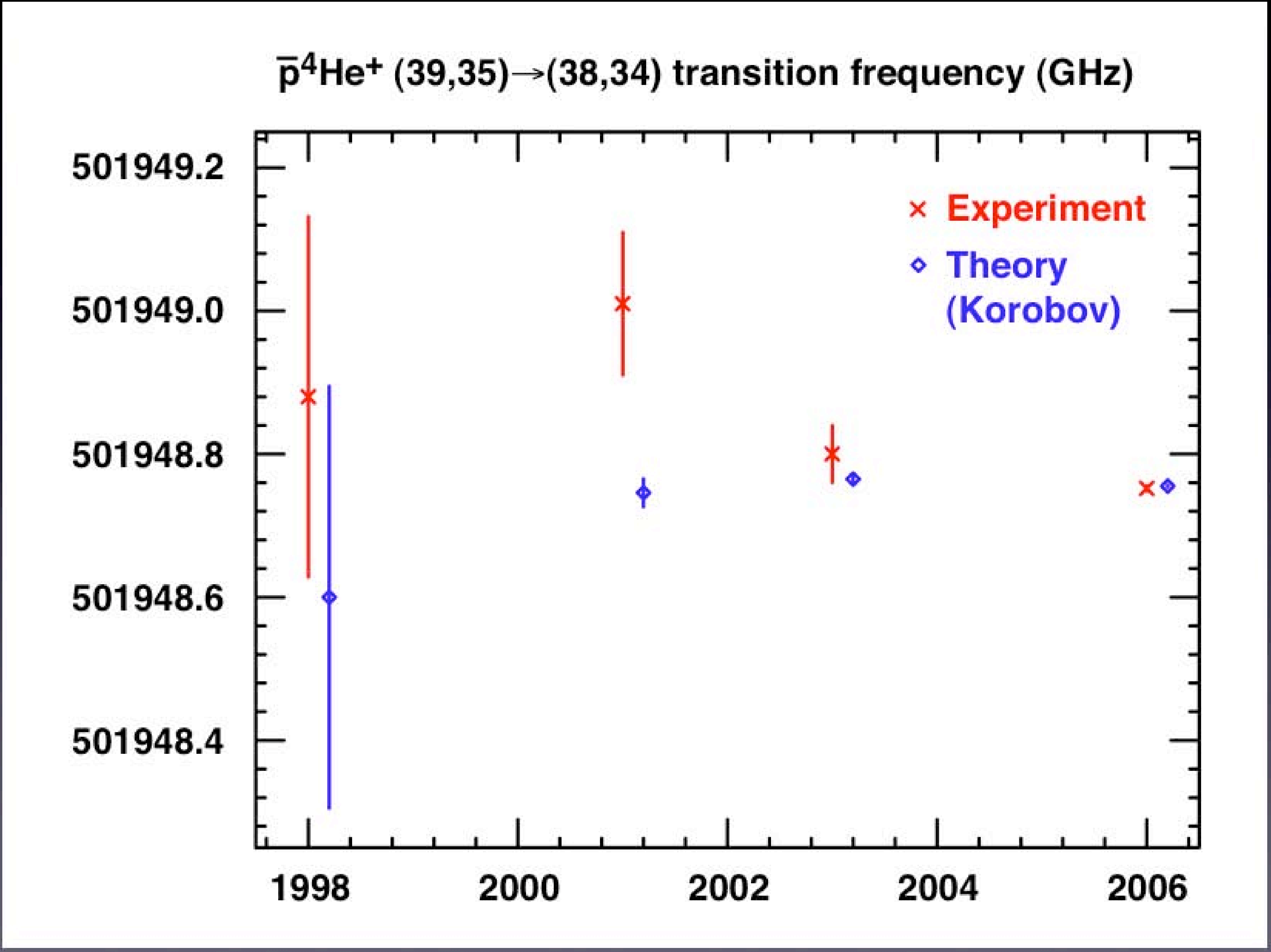
(39,35) → (38,34) example (Korobov)

E_{nr}	$=$	501 972 347.9	
E_{rc}	$=$	−27 525.3	
E_{rc-qed}	$=$	233.3	
E_{se}	$=$	3 818.0	
E_{vp}	$=$	−122.5	$\Delta E_{\rm vp} = \frac{4 z_i \alpha^3}{3 m_3^2}\left[-\frac{1}{5} + (z_i\alpha)\pi\frac{5}{64}\right]\langle\delta(\boldsymbol{r}_i)\rangle,$
E_{kin}	$=$	37.3	$\Delta E_{\rm kin} = \alpha^2\left\langle -\frac{\boldsymbol{\nabla}_1^4}{8m_1^3} - \frac{\boldsymbol{\nabla}_2^4}{8m_2^3} + \frac{(1+2a_2)z_2}{8m_2^2}4\pi\delta(\boldsymbol{r}_2)\right\rangle,$
E_{exch}	$=$	−34.7	$\Delta E_{\rm exch} = -\alpha^2\frac{z_i}{2m_i m_3}\left\langle\frac{\boldsymbol{\nabla}_i\boldsymbol{\nabla}_3}{r_i} + \frac{\boldsymbol{r}_i(\boldsymbol{r}_i\boldsymbol{\nabla}_i)\boldsymbol{\nabla}_3}{r_i^3}\right\rangle,$
E_{α^3-rec}	$=$	0.8	$\Delta E^{(3)}_{\rm recoil} = \frac{z_i\alpha^3}{m_i m_3}\left\{\frac{2}{3}\left(-\ln\alpha - 4\beta + \frac{31}{3}\right)\langle\delta(\boldsymbol{r}_i)\rangle - \frac{14}{3}\langle Q(r_i)\rangle\right\},$
$E_{two-loop}$	$=$	0.9	$\Delta E_{\rm two\text{-}loop} = \alpha^4\frac{z_i}{m_3^2\pi}\left[-\frac{6131}{1296} - \frac{49\pi^2}{108} + 2\pi^2\ln 2 - 3\zeta(3)\right]\langle\delta(\boldsymbol{r}_i)\rangle$
E_{nuc}	$=$	2.4	$\Delta E_{\rm nuc} = \frac{2\pi z_i (R_i/a_0)^2}{3}\langle\delta(\boldsymbol{r}_i)\rangle,$
E_{α^4}	$=$	−2.6	$\Delta E_{\alpha^4} \approx -\alpha^4\frac{\pi}{2}\delta(\boldsymbol{r}_1).$
E_{total}	$=$	501 948 755.6(1.3) MHz	

結果

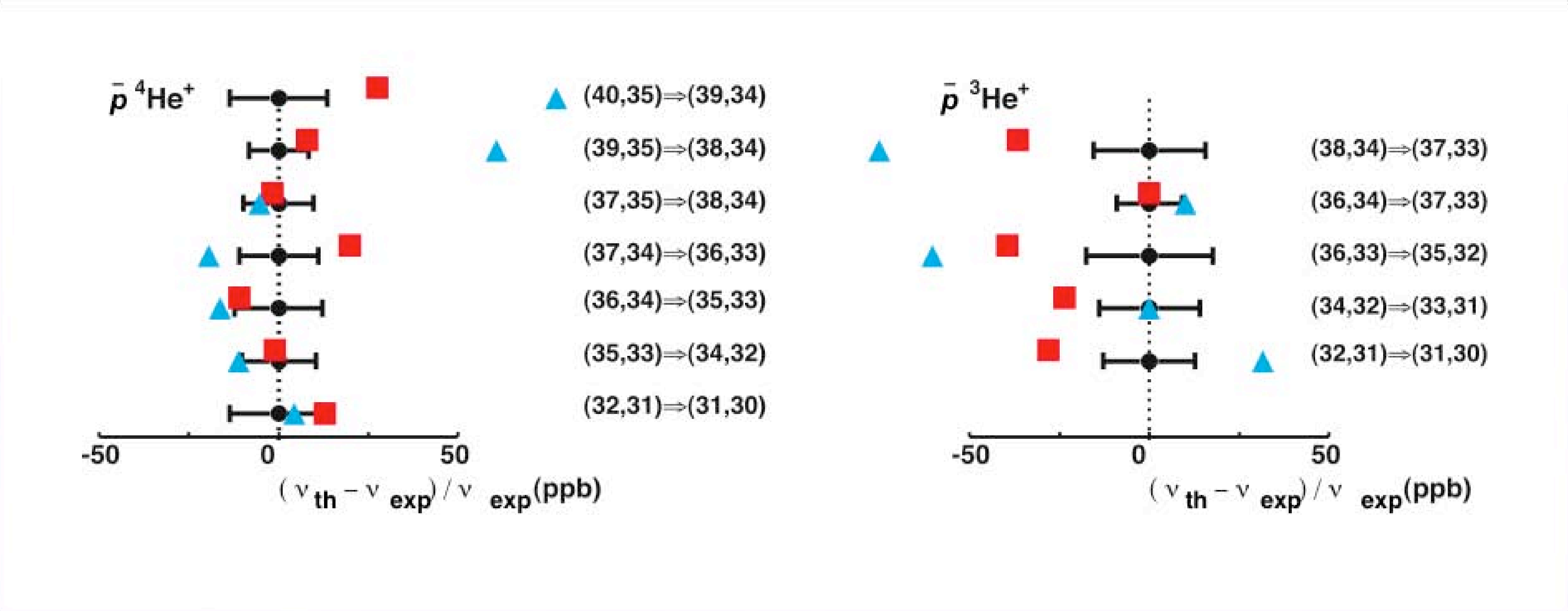
Results & Implications

Experimental & theoretical precisions improved



Exp vs Theory

Two theory calculations (▲and■)



- **Up to ~50 ppb differences between the two theoretical calculations (▲ and ■) ; we now take ■ in view of the claimed accuracy**
- **Systematic shift of some 20 ppb in $\overline{p}{}^3He$?**

Errors

σ_{exp} = 4-15 MHz

statistical 3-13 MHz,

systematic: chirp 2-4 MHz, collisional shifts 0.1-2 MHz, harmonic generation 1-2 MHz

(and negligible AC-Stark)

σ_{theory} = 1-2 MHz (Korobov)

$$m_{\bar{p}}/m_e = 1836.152674$$

$$\pm 0.000005$$

ASACUSA2006
PRL 96, 243401 (2006)

$$m_p/m_e = 1836.15267261$$

$$\pm 0.00000085$$

codata2002

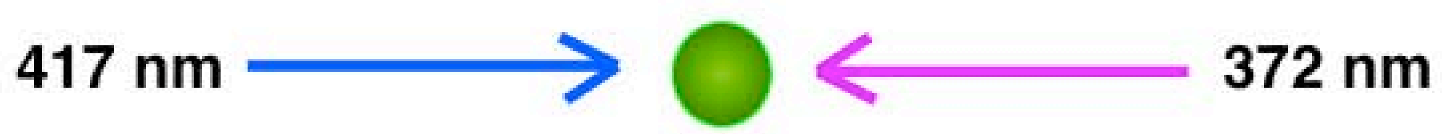
2007

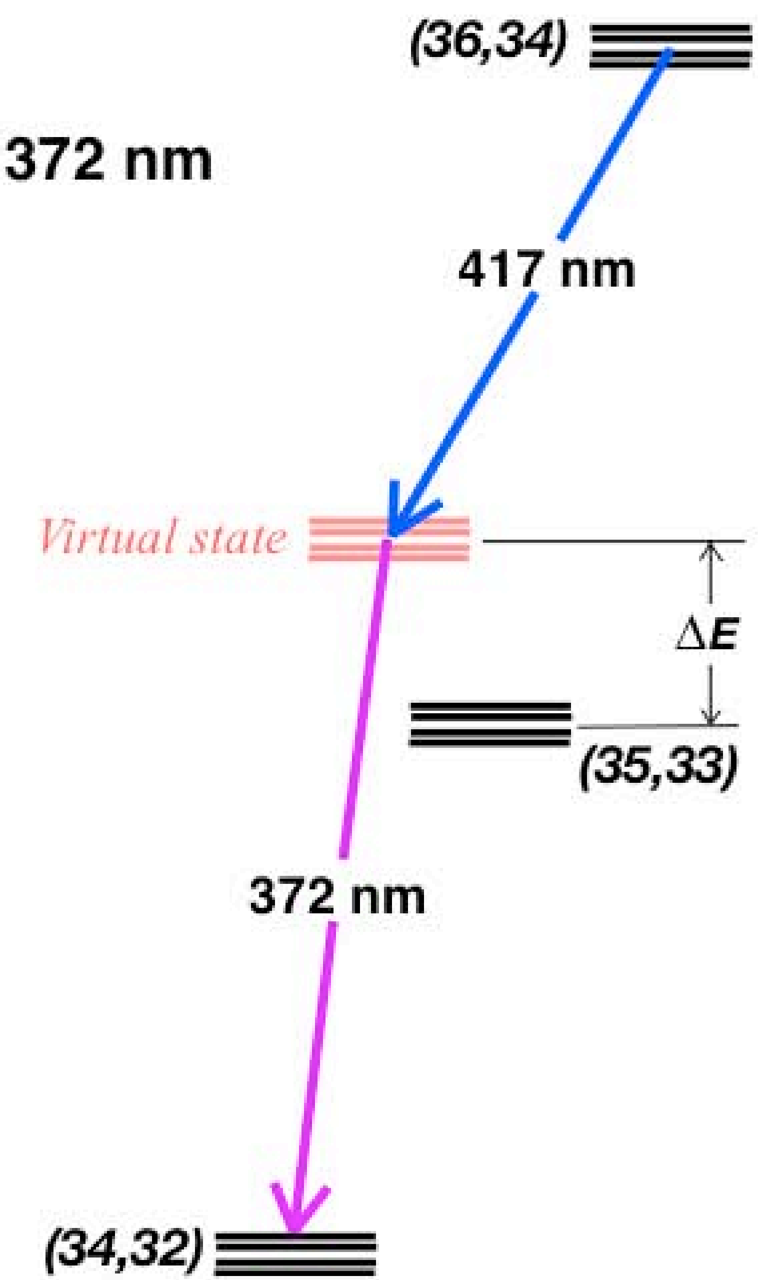
ongoing effort

幅の要因	
自然幅	15MHz - 150kHz
~~Fourier幅~~	~~パルスレーザー~~ ~~パルス長~~
~~衝突~~	~~RFQD~~
ドップラー幅	2光子分光
~~レーザー単色性~~	~~パルスレーザー~~ ~~→CWレーザー~~

シフトの要因	
~~衝突~~	~~RFQD~~
~~チャープ~~	~~~2MHz,~~ ~~パルスレーザー不可避~~
~~周波数較正~~	~~光周波数comb~~
AC Stark	∝ Power
（理論）	~MHz?

Sub-Doppler two-photon laser spectroscopy

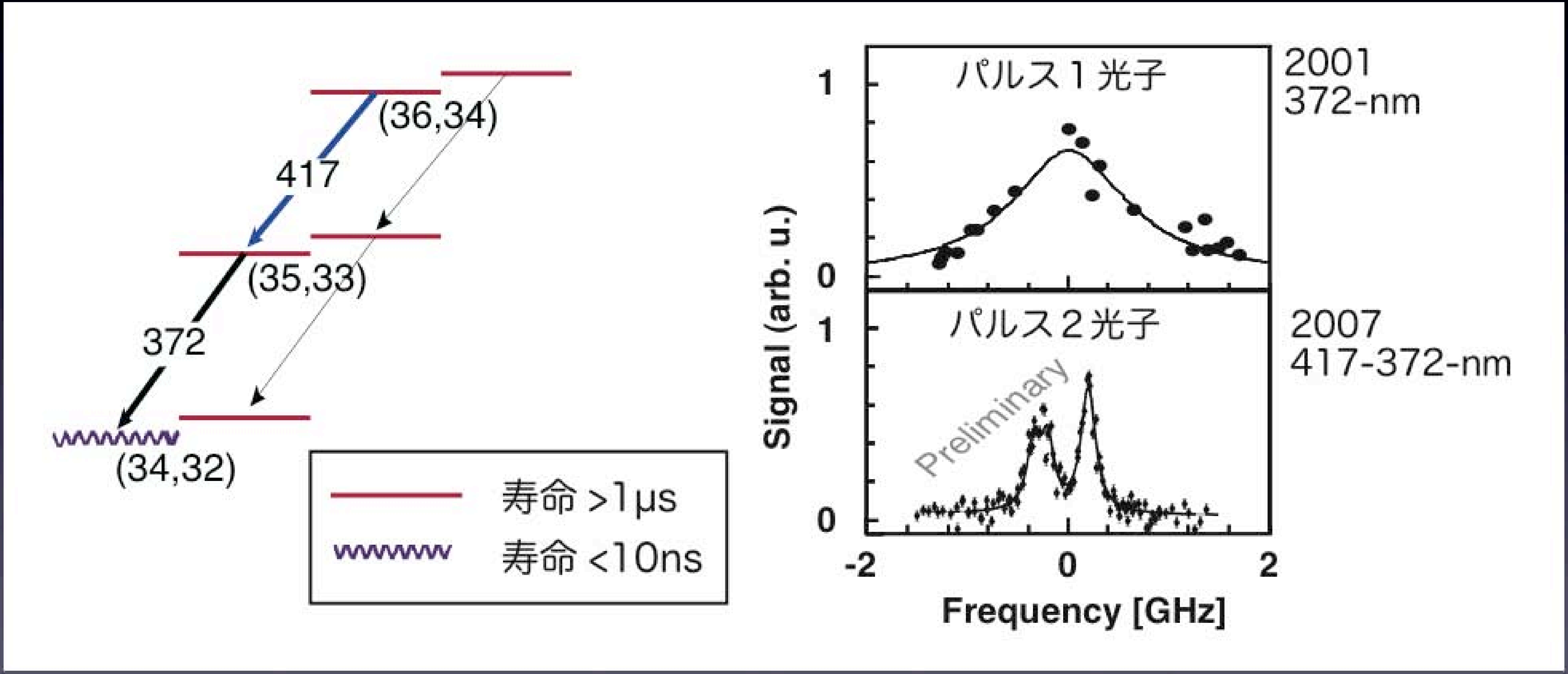


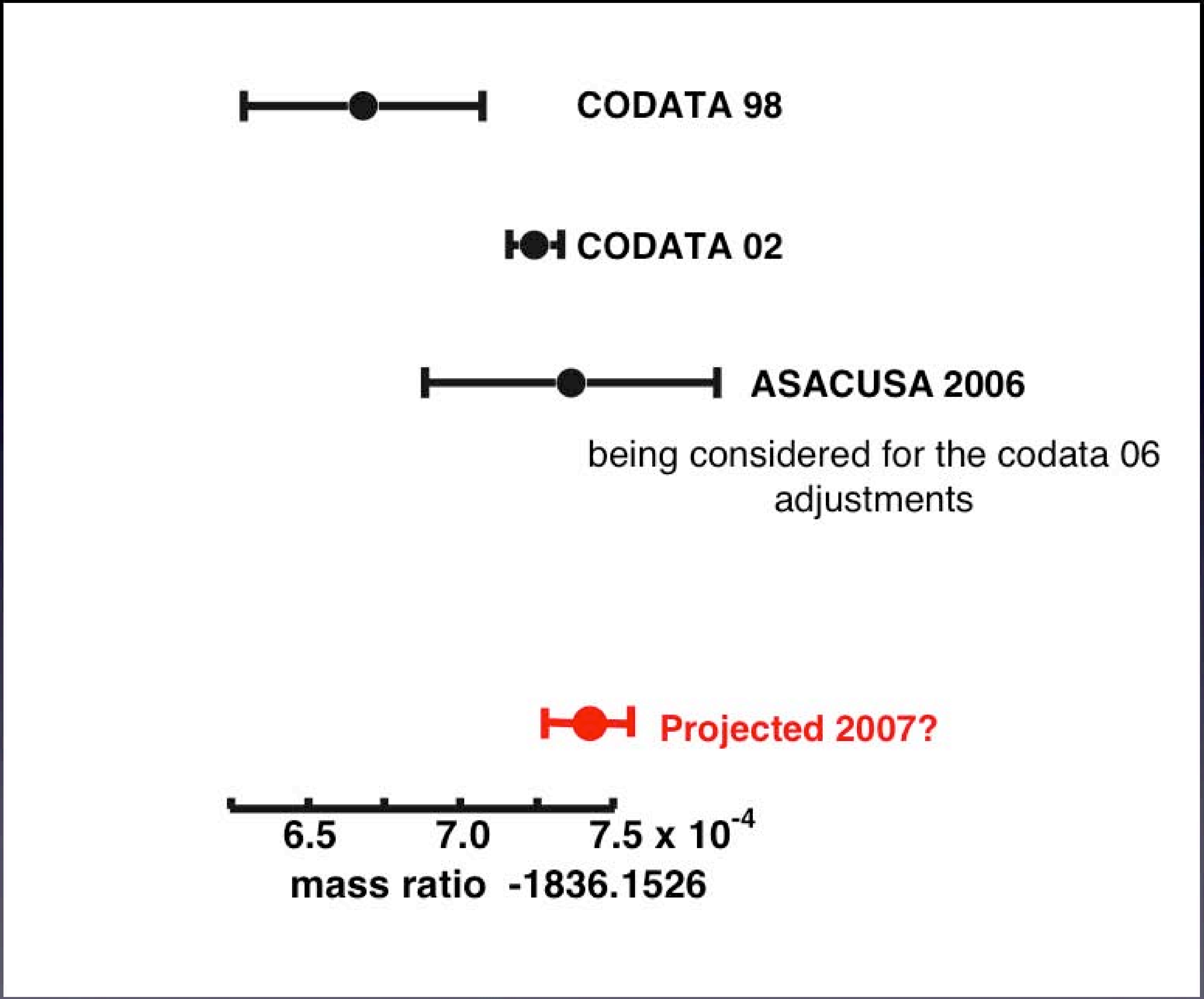


Doppler width decreased
from 1300 MHz to 70 MHz

$$\Gamma = \frac{|\nu_1 - \nu_2|}{\nu_1 + \nu_2} \times 2.35(\nu_1 + \nu_2)\sqrt{\frac{kT}{M}}$$

線幅大幅に減少


(36,34)
417
(35,33)
372
(34,32)
寿命 >1μs
寿命 <10ns
パルス１光子
2001
372-nm
パルス２光子
2007
417-372-nm
Preliminary
Signal (arb. u.)
1
0
1
0
-2
0
2
Frequency [GHz]


CODATA 98
CODATA 02
ASACUSA 2006
being considered for the codata 06 adjustments
Projected 2007?
6.5
7.0
7.5 x 10-4
mass ratio -1836.1526

パルスレーザーの限界に達した

次

まだまだやるぞ

パルスレーザーをやめるしかない

幅の要因	
自然幅	15MHz - 150kHz
~~Fourier幅~~	~~パルスレーザー~~ ~~パルス長~~
~~衝突~~	~~RFQD~~
~~ドップラー幅~~	~~2光子分光~~
~~レーザー単色性~~	~~パルスレーザー~~ ~~→CWレーザー~~

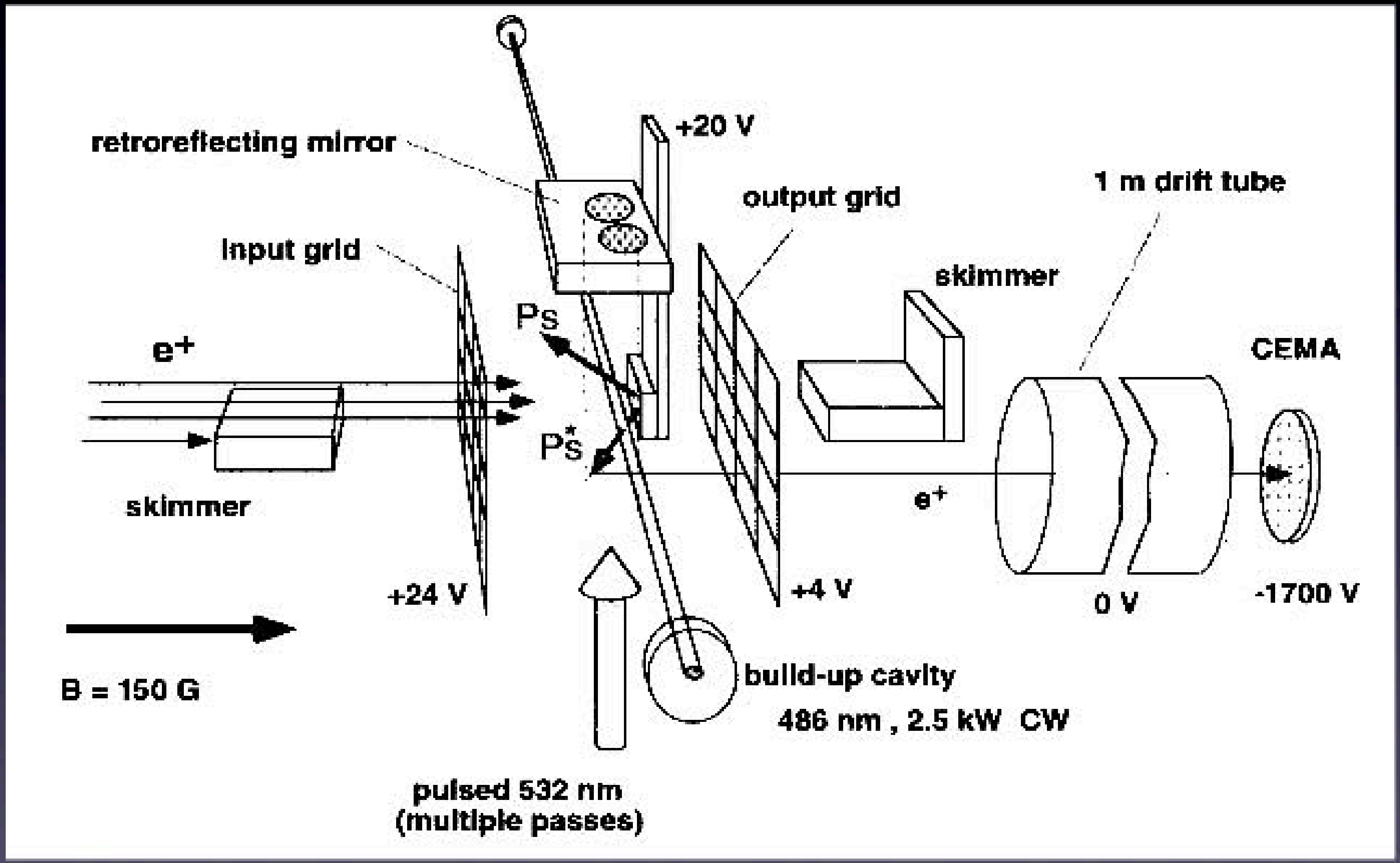
シフトの要因	
~~衝突~~	~~RFQD~~
チャープ	~2MHz, パルスレーザー不可避
~~周波数較正~~	~~光周波数comb~~
AC Stark	∝ Power
(理論)	~MHz?

エキゾチック原子のレーザー分光

μ^+e^-	meyer et al, PRL 84 (2000) 1136	pulse	2455528941.0(9.8)
e^+e^-	Danzmann et al, PRA 39 (1989) 5072	pulse	1233607218.9(10.7)
e^+e^-	Fee et al, PRA 48 (1993) 192	CW	1233607216.4(3.2)
μ^- p	PSI in progress	pulse	no signal yet
$(\mu^-\,He)^+$	Zavattini et al	pulse	questionable
$\bar{p}He$	ASACUSA	pulse, so far	2007 very preliminary 1553643100.0(5.0)

the only exotic atom studied by a CW laser system so far... e^+e^-

M.S. Fee et al, Phys. Rev. A 48 (1993) 192

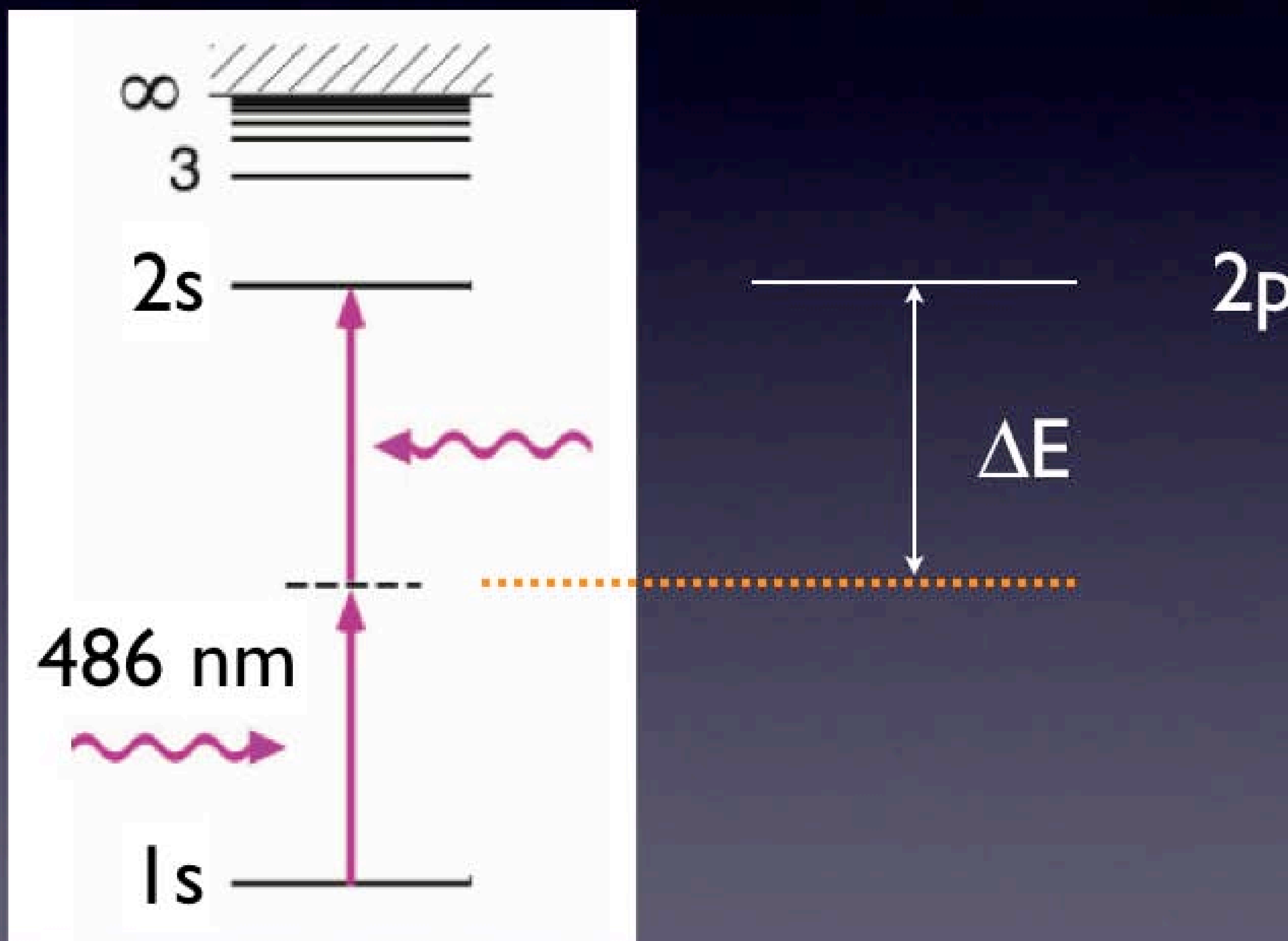


2.5 kW CW laser power, power density 1.7 MW/cm^2

これはパルスレーザー顔負けの大強度だ...

巨大パワーが必要な理由

power density $\propto \Delta E$



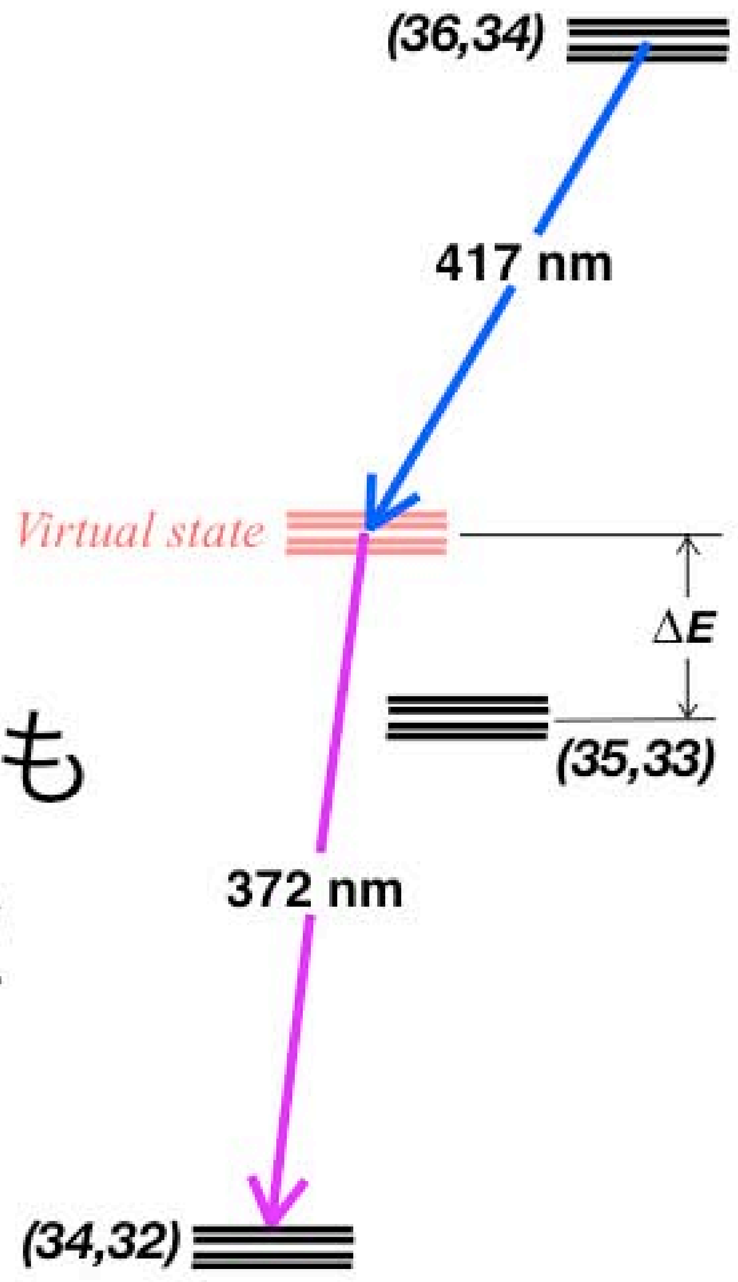
しかしluckyなことに我々は$\Delta E \to 0$にできる

パワー密度$\propto \Delta E$

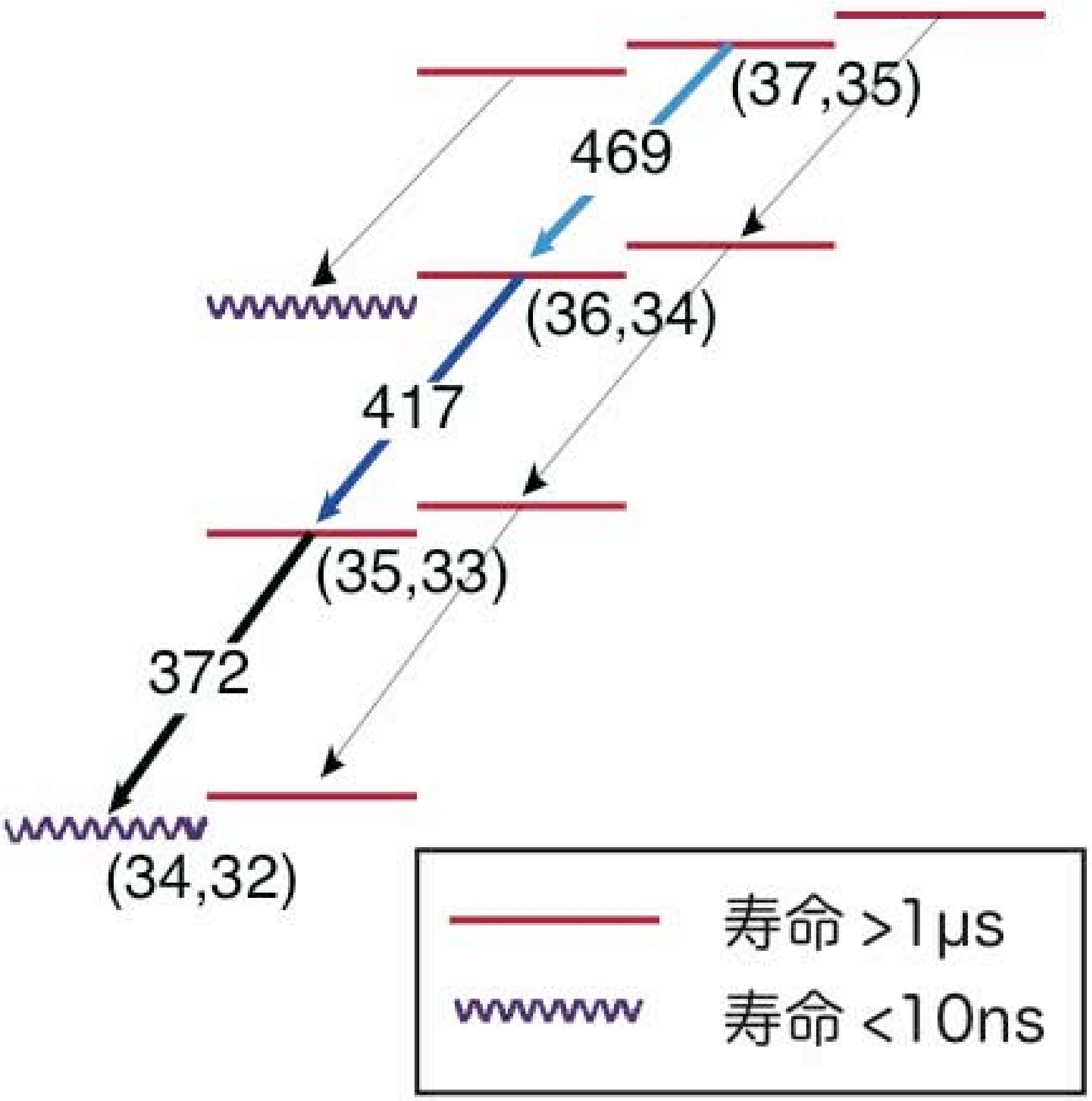
$\Delta E \to 0$とすると

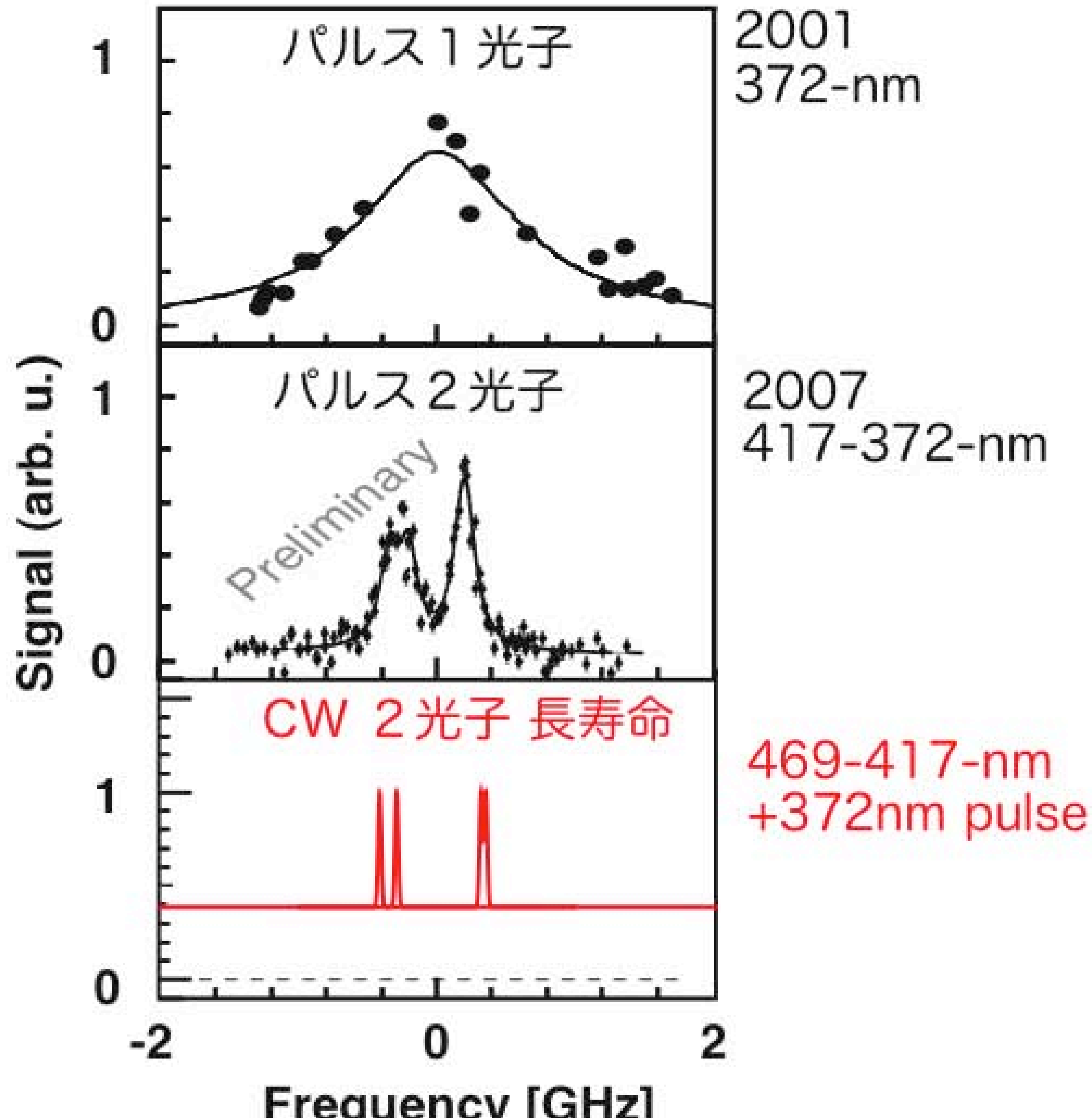
CWレーザーでも可能かも

$<100 W/cm^2$でよさそうだ

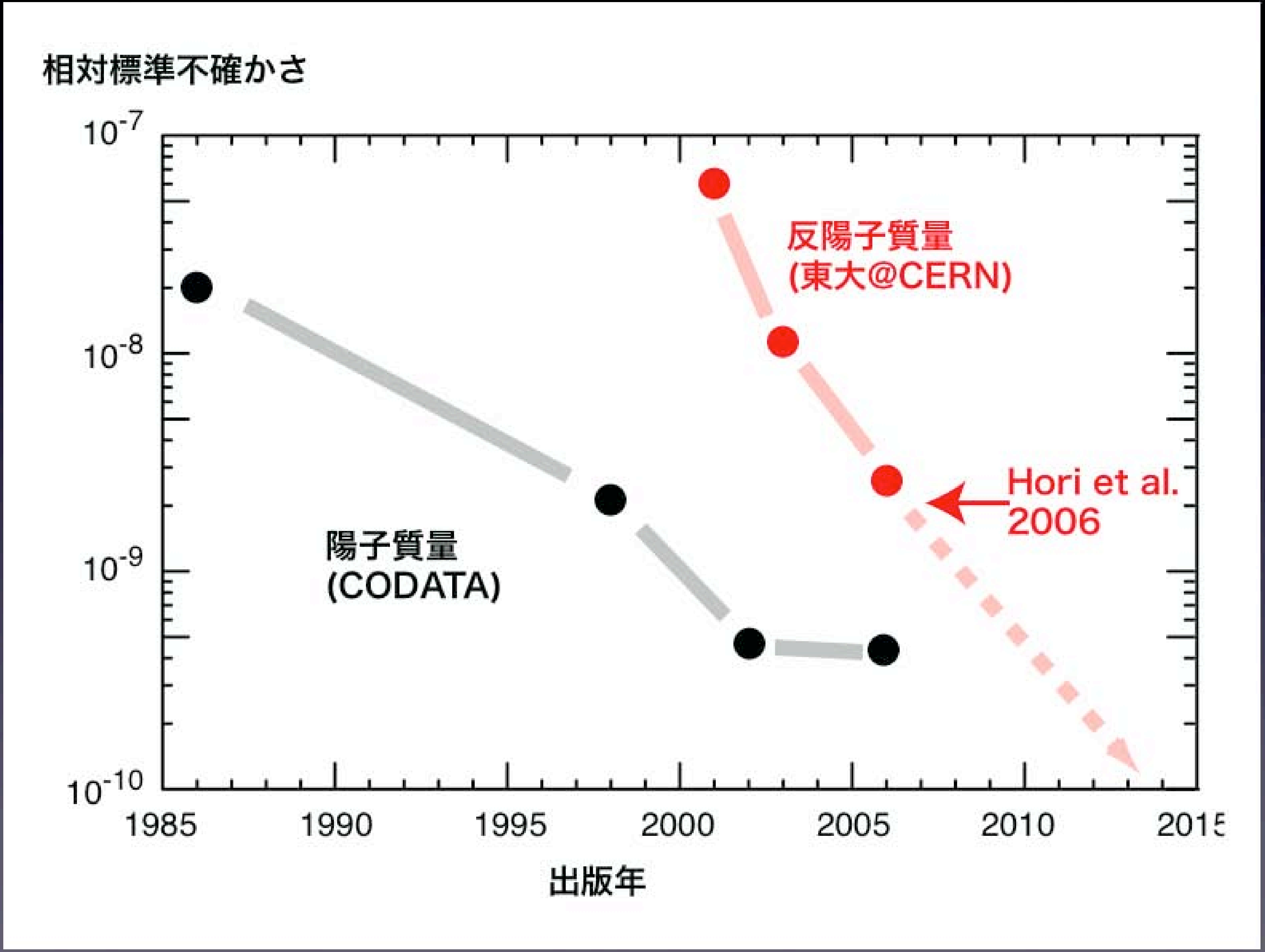


究極の実験
CW, 二光子, 準安定準位間遷移





antiproton mass may become better known



density shift

RFQD

Comb

2-photon
CW

結

summary

Serendipitous discovery

Precision of $\bar{p}$He spectroscopy has reached 10^{-9}
(RFQ, Comb, ..., took us a long time)

x100 improvement possible (nontrivial but doable),

Update the fundamental constant (m_p/m_e)

but

Must better understand 3-body QED calculations

Masaki Hori, EURYI 受賞
(European Young Investigator Awards)

賞金 2億円で独立研究グループを作る